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DESIGN, CONSTRUCTION, AND PRELIMINARY COMBUSTION TRIALS OF A RIG TO EVALUATE RESIDUAL FUEL-OIL/WATER EMULSIONS

R. E. Barrett, et al

Battelle Memorial Institute

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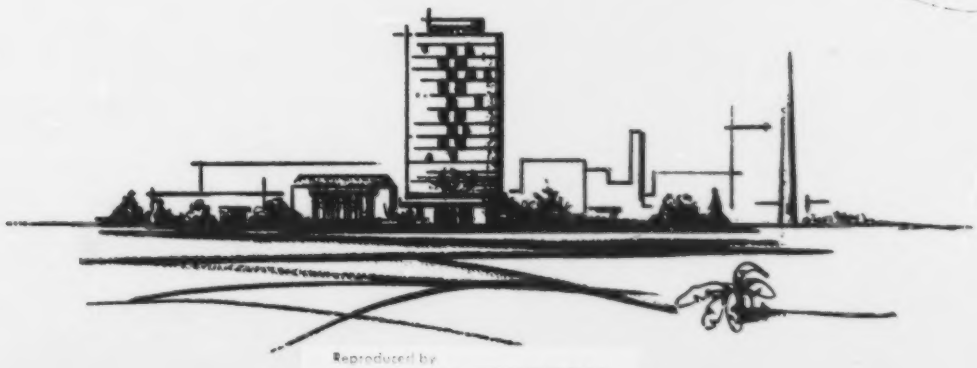
RESEARCH REPORT

DESIGN, CONSTRUCTION, AND PRELIMINARY
COMBUSTION TRIALS OF A RIG TO
EVALUATE RESIDUAL FUEL-OIL/WATER EMULSIONS

Contract No. PH 86-68-84
Task Order No. 22

to

NATIONAL AIR POLLUTION CONTROL ADMINISTRATION
Division of Process Control Engineering



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SUMMARY REPORT

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July 15, 1970

by

R. E. Barrett, H. R. Hazard,
C. McComis, and D. W. Locklin

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16. Abstracts

This task report describes the design and development of a versatile combustion-test rig for investigating combustion of residual fuel oils at conditions simulating either the residence time or turbulence level of combustion in industrial boilers. The rig was designed to permit adjustment of the following factors: excess air, firing rate, combustion-air swirl, atomization-nozzle type, atomization temperature, fuel, and wall temperatures (with cooling surface added).

Successful operation of the rig was achieved at firing rates of about 1.8 and 7.0 gph with No. 6 residual fuel oil and a 20 percent water-in-residual fuel oil emulsion. Fuel preheat for atomization was varied from 180 F to 250 F. Smoke numbers (Bacharach) are reported for a number of combustion trials at 2 to 30 percent excess air. When firing No. 6 fuel oil, No. 1 smoke could be obtained at excess air levels of below 10 percent. Preliminary measurements indicated that NO_x levels were about 400 ppm when firing No. 6 fuel oil and about 100 ppm when firing a 20-percent-water emulsion.

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INTRODUCTION

The Division of Process Control Engineering of the National Air Pollution Control Administration is presently evaluating methods of reducing air-pollutant emissions from combustion devices fired with both distillate and residual fuel oil. Results of several phases of the distillate fuel oil program have been published by NAPCA.[1-3]* These publications have discussed the effects of air-fuel ratio, residence times, and additives on pollutant emissions from a residential-type 1-gph pressure-atomizing burner firing commercial No. 2 fuel oil. Other NAPCA efforts in this area have included investigating the effects of flame-retention heads on emissions from domestic oil burners.[4]

In conjunction with this program, NAPCA became interested in evaluating emulsified oil-water fuels as a result of improved combustion (evidenced by shorter combustion times) reported by other investigators. The concept of firing fuel oil-water emulsions to obtain secondary atomization and, therefore, improve combustion was advanced by Ivanov and others[5] in 1957, and further discussed by Ivanov and Nefedov[6] in 1962. In the desired type of oil-water emulsion, each fuel oil droplet contained one or more small droplets of water. As a drop of emulsion was introduced into a hot chamber, they observed that the pressure

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* References are listed on page 38.

generated within the fuel droplet by the vaporizing water was sufficient to rupture the fuel droplet in a miniature explosion. This shattering or secondary atomization of the fuel droplet produced further reduction in the effective droplet size and exposed a greater surface area of fuel for vaporization, mixing, and burning, thus provided more rapid and improved combustion.

In a previous program task conducted at Battelle-Columbus[7], a method for preparing stable water-in-distillate fuel oil emulsions was developed and these emulsions were fired in a burner similar to that used by NAPCA. In subsequent work at the NAPCA Division of Process Control Engineering, measurements showed evidence that emulsification of water in No. 2 fuel oil could reduce NO_x emissions.

In view of the potential benefits of emulsified fuel oils for improving combustion and, consequently, lowering emissions, NAPCA extended its interest in emulsified fuels to include residual fuel oil. Battelle supported this NAPCA program in a task order that included the development of techniques for preparing water-in-residual fuel oil emulsions.[8] As a second part of that task order, Battelle prepared the preliminary design of a laboratory-scale residual-oil-fired combustion test rig. Included in the consideration for this design was an analysis of scaling and modeling phenomena for combustion systems.

The work described here was an extension of the preliminary design of the combustion test rig to include final design, construction, development, and trial firing of the rig.

TASK OBJECTIVE

Battelle's assignment under this task order was to design and construct a laboratory-scale combustion rig to fire residual fuel oil at low firing rates, approximately 2.0 gph. The rig was to incorporate the range of adjustability needed to simulate combustion conditions in industrial boilers. In addition,

limited trials were to be made with the rig to establish the overall suitability of the design and a few emission measurements were to be taken to provide a preliminary and partial judgment of the effectiveness of emulsions in reducing emissions.

SUMMARY AND CONCLUSIONS

A combustion test rig, essentially as described in the earlier task order report[8], was constructed and fired at a variety of conditions. The burner for this rig was designed to be quite versatile to permit establishing good combustion under a variety of conditions. Because one purpose of the unit was to permit evaluation of emulsions and additives for improving combustion and reducing emissions, it was desirable to have sufficient flexibility of operation to provide a range of combustion performance, including both high and low smoke levels at a given value of excess air. Therefore, in addition to the conventional adjustments of firing rate, excess air, fuel, and fuel temperature, this rig was designed to permit varying the degree of swirl imparted to the combustion air and to permit use of several types of atomizing nozzles.

The unit was fired at the following conditions:

(1) Firing rates of 1.8 and 7.0 gph.
(2) Excess air range from 2 to 30 percent.
(3) Fuel temperature of 180 F, 220 F, and 250 F.
(4) Air-atomizing and pressure-atomizing fuel nozzles.
(5) Combustion air either all swirl, all axial, or a combination of swirl and axial.
(6) Fuel types - No. 6 residual fuel oil and an emulsion of 20-percent water in residual fuel oil.
(7) With cooled surfaces in the furnace to lower gas and wall temperatures.

The scope of this task order was primarily intended to include design and development of a burner. As a part of the development, a limited number of combustion trials were conducted in the furnace while varying the parameters listed above. Data from these trials permitted the following observations to be made:

(1) Bacharach No. 1 smoke could be achieved regularly at 10-percent excess air.

(2) An air-atomizing nozzle fired at a rate higher than its design capacity appeared best for firing at low rates.

(3) Either all-swirl or all-axial combustion air gave cleaner combustion than the combination of swirl-and-axial flow.

(4) At 5 to 10 percent excess air, the emulsion produced cleaner combustion (less smoke) than the residual fuel oil and also produced less NO_x.

(5) Little effect on smoke was noted due to fuel temperature.

(6) Adding cooling surfaces had the effect of producing increased smoke emissions.

Again, it should be cautioned that these conclusions are based on limited trials and a much more extensive combustion program would be needed to confirm these results. NAPCA is planning to utilize the combustion rig developed in this program to conduct this larger program.

COMBUSTION TEST RIG DESIGN

The design of the combustion test rig to fire residual fuel oil at low firing rates followed closely the preliminary design described in an earlier report.[8] Figure 1 shows the combustion test rig as set up for operation in the Battelle-Columbus Combustion Laboratory.

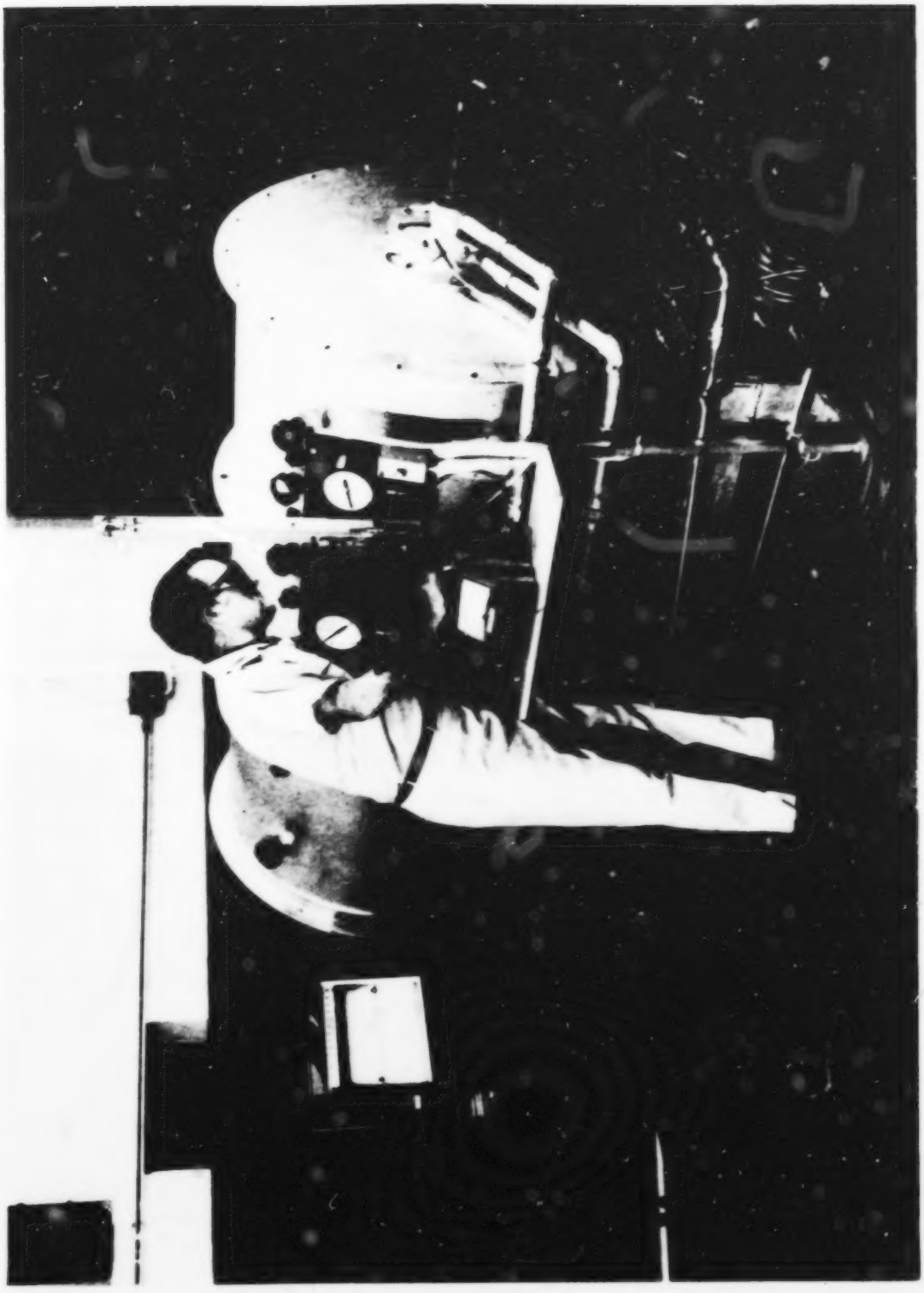

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FIGURE 1. LABORATORY-SCALE COMBUSTION TEST RIG

A combustion rig of the type described below is sufficiently versatile to have a wide variety of uses. Possible uses of this rig include studies of the effect of combustion variables such as droplet size, air-fuel ratio, and external recirculation of flue gas on pollutant emissions. With the addition of controlled-temperature heat-transfer tubes, the rig would also be useful for studying the effects of additives on superheater tube corrosion and deposits. To simulate time-temperature gradients to lower temperatures, as encountered in passes through the boiler heat-transfer surfaces, the furnace length should be extended and/or cooling surface added to obtain gas cooling at the desired rate.

Burner Design

The combustion test rig being designed for this task has two unique requirements, namely: (1) firing residual fuel oil at low rates, and (2) simulating combustion conditions in industrial boilers. Therefore, it was important that the burner be flexible enough to permit operation over a range of conditions. Such factors as combustion air swirl, combustion air pressure drop, atomizer type and size, and atomizer location should be adjustable.

Figure 2 is a cross-section drawing of the burner that was designed for this rig. It is similar to the burner described in the earlier report.[8] Details of burner construction will be presented in the Appendix.

Using this burner design, it is possible to vary the firing rate, flame velocity, swirl angle, type of fuel burner, atomizer type and size, and atomizer location relative to the air admission path. Combustion air may be admitted through openings between 12 vanes positioned to give the air a high degree of swirl, it may be admitted through axial holes in the plate behind the burner throat in Figure 3 to provide axial flow, or a combination of swirl and axial air may be used. In the latter case, adjustment of the proportion of air flow to the swirl vanes and to the axial holes varies the percentage of swirl in the burner throat.

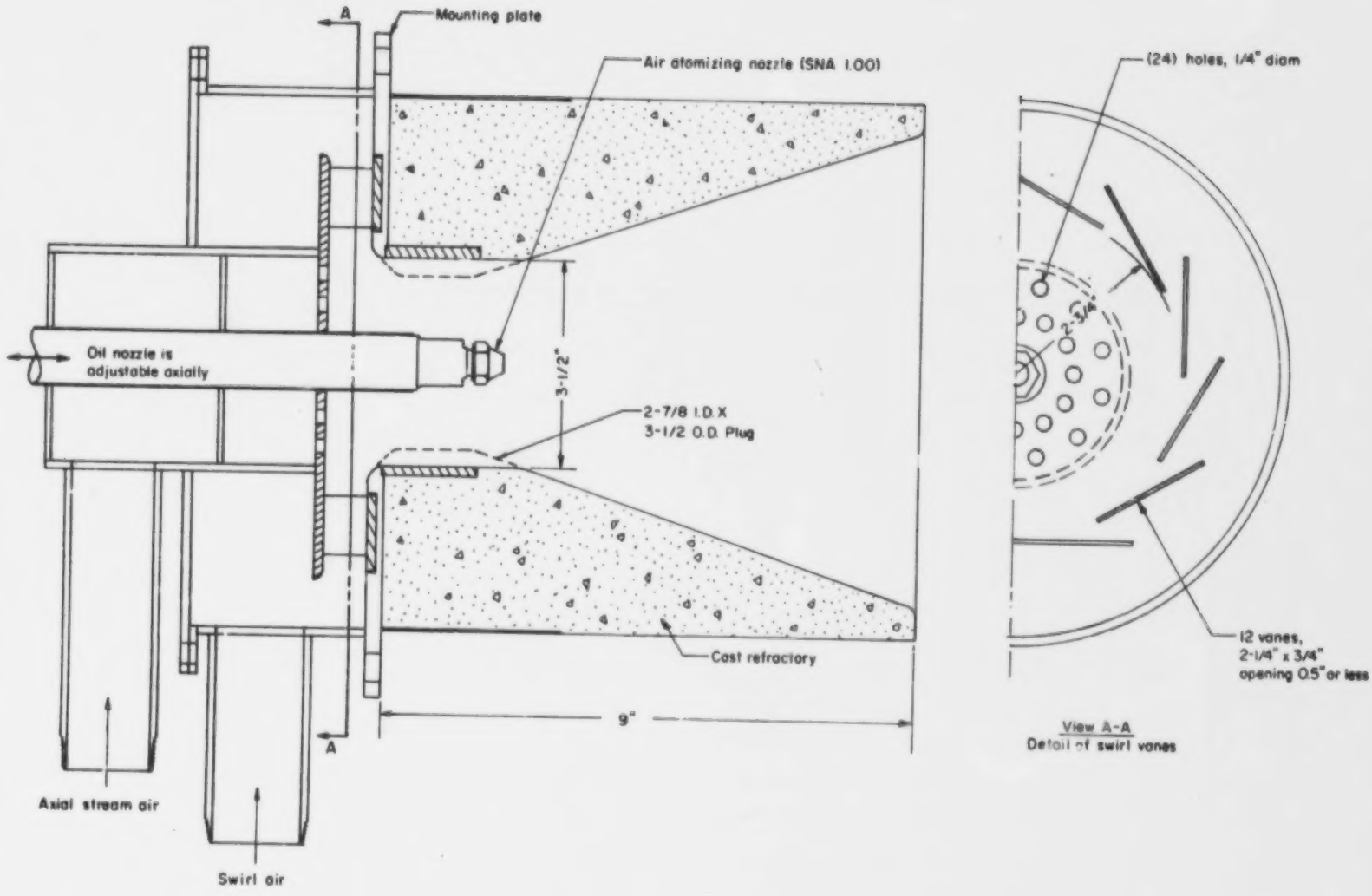

FIGURE 2. BURNER FOR COMBUSTION RIG

See Figure 20 for details.

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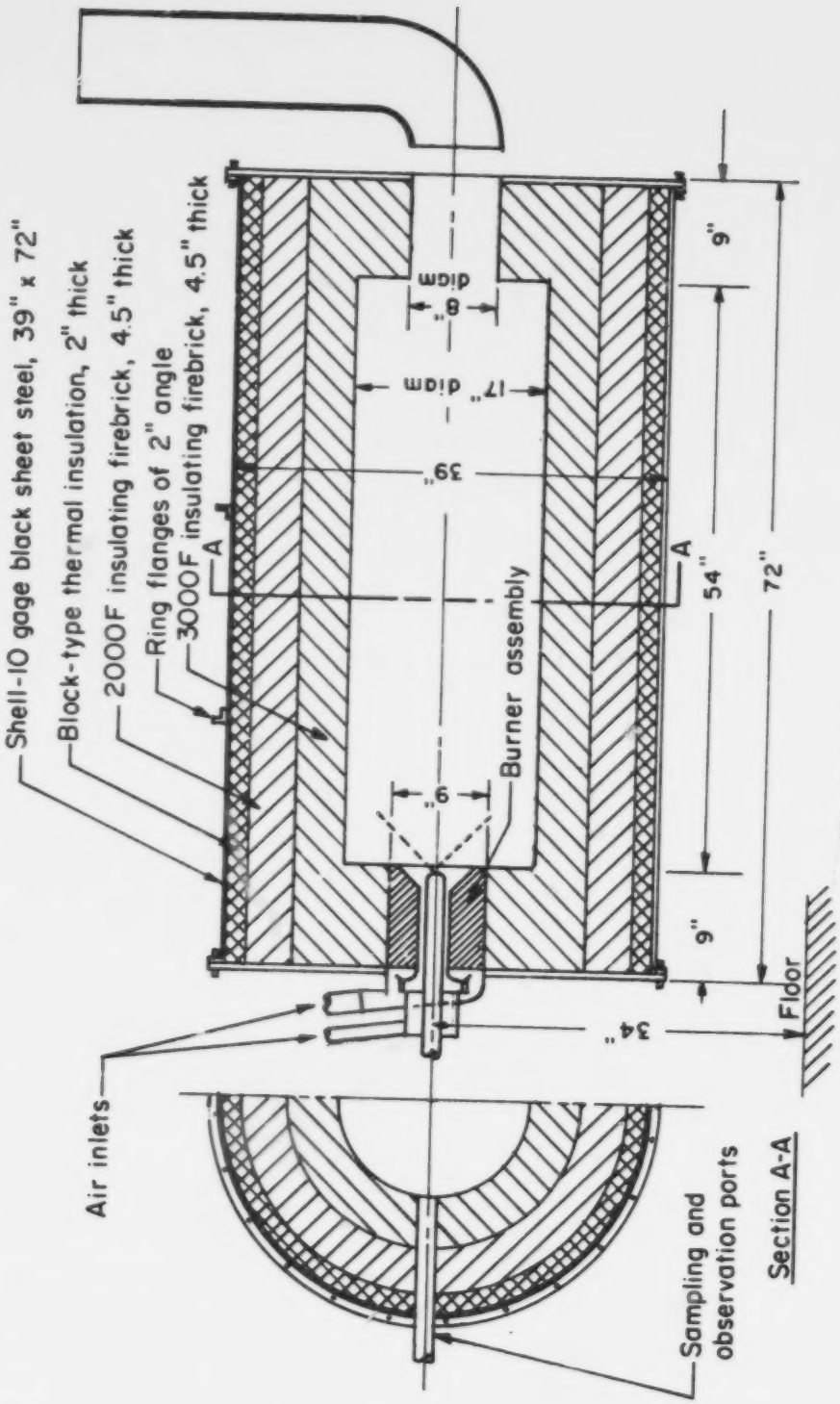


FIGURE 3. FURNACE SECTION OF COMBUSTION RIG

The turbulence level in the axial stream will be relatively high because air is admitted at a velocity of about 120 fps or more through 24 holes; the jets from these holes will merge in the burner throat to provide a highly turbulent stream at low axial velocity. Because of the high turbulence from the axial-flow holes, the overall turbulence level remains about the same (at the same firing rate and excess air) as the swirl is reduced. Air flows to the swirl-air plenum and the axial-air plenum are separately manifolded, controlled and measured.

The burner throat of a 3.5-inch diameter is designed for an axial velocity of 15 fps, to produce a large flame that will fill the furnace. This flame should simulate residence times in the flame region that are comparable to residence times in the flame of industrial boiler furnaces.

To simulate velocities in a full-scale boiler burner, two alternatives are available. First, the firing rate can be increased by a factor of five (to 8 gph) with no other changes. The flame size and shape will be about the same as with the low firing rate due to the much higher turbulence, but the residence time will be reduced by a factor of five. Alternatively, an insert can be placed in the burner throat (see Figure 2), reducing its diameter from 3.5 inches to 2.875 inches. (This insert can be a metal ring held in place by set screws.) The throat velocity, with this change, will increase by the required factor of about 5 so that full prototype velocity will be obtained at the 1.6 gph firing rate. With this change, the flame should become smaller and will not fill the combustion space. Again, residence time in the flame region will be reduced.

A variety of fuel nozzles of the air-atomizing, steam-atomizing, or pressure-atomizing types may be fitted to the nozzle holder.

It is possible to fire natural gas in this burner by replacing the fuel nozzle assembly with a gas injector. Pulverized coal could also be fired by substituting a coal nozzle for the oil atomizer. The coal nozzle would

require a central cone to form a conical coal dispersion much like an oil spray. In a previous furnace of this size at Battelle, coal was fired at rates from 50 to 100 lb/hr.

Furnace Design

Figure 3 is a section view of the furnace for the combustion test rig. The cylindrical combustion chamber cavity of the furnace is 17 inches in diameter and 54 inches long. The furnace is lined with 2 layers of firebrick and is insulated as follows: an inner layer of 2900 F insulating firebrick 4.5 inches thick, a middle layer of 2000 F insulating firebrick 4.5 inches thick, and the outer layer of 2-inch block-type insulation. A 10-gage steel air-tight outer shell encloses the furnace and is 39 inches in diameter and 72 inches long.

Several observation and sampling ports are provided along one side of the furnace for observing the flame and providing for traversing across the flame at various distances from the burner. At the outlet, the diameter of the furnace is reduced to 8 inches to enclose the flame, provide for normal recirculation, and to limit radiation loss to normal values.

For the limited firing at Battelle included in this task order, the exhaust duct was simplified to a single 12-inch-diameter metal duct. A gap was left between the furnace outlet and the exhaust inlet. This opening permitted room air to enter the exhaust duct and dilute the combustion products, thus preventing overheating of the exhaust duct. For a more permanent installation and for extended tests, it would be desirable to provide a heavier duty exhaust system, possibly including a heat exchanger. The entire furnace was mounted on skids.

Laboratory Setup

Figure 4 shows a schematic layout of the laboratory setup in Battelle's Combustion Laboratory for firing residual fuel oil in the combustion test rig.

Air Systems. Compressed air was used as the supply for both atomizing and combustion air. Atomizing air pressures ranged from 5 to 30 psig. Two parallel air flowmeters and control valves were used to control air flow to the two burner air inlets (swirl and axial). Total air flow at the low firing rate (about 1.8 gph) of residual oil was about 40 to 50 cfm at a plenum pressure of up to 1.0 inches of water for all-swirl air and up to 3.0 inches of water for all-axial air. NAPCA may want to consider using a blower instead of compressed air to supply combustion air for their installation.

Fuel System. An adjustable-flow positive-displacement pump was used to supply and meter the fuel at a constant volumetric flow rate. Fuel flow was determined by pump calibration and confirmed by weighing. Preheating of the fuel was provided at 3 locations:

(1) The fuel weighing tank where the fuel was warmed by a steam coil to 150 F to 170 F.
(2) A steam heat exchanger where the fuel was heated to 190 F.
(3) A steam-jacketed nozzle holder, 12 inches long, to isolate hot fuel from cold air and to ensure that the fuel was at the desired temperature for atomization as indicated by a thermocouple at the fuel nozzle.

All fuel lines were insulated to minimize heat loss. Alternatively, thermostated electric heaters could be substituted for steam heating in the two fuel tanks, and a pressurized water or mineral oil system could be used to maintain nozzle temperatures.

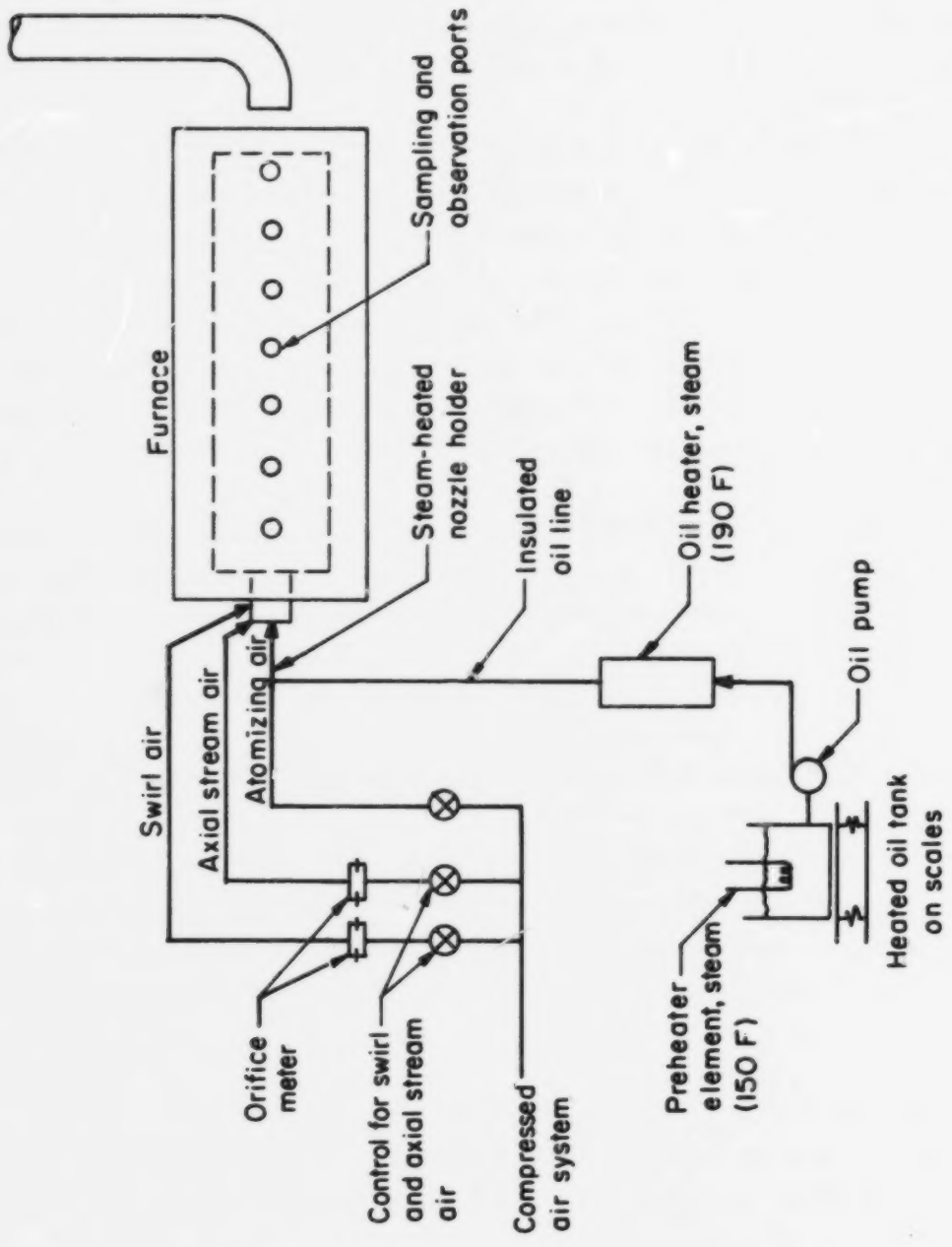


FIGURE 4. LABORATORY SETUP FOR FIRING RESIDUAL FUEL OIL IN THE COMBUSTION TEST RIG

Sampling and Analysis Equipment. Because the firing trials of the rig were to be quite limited, only minimal effort was devoted to the sampling and analysis equipment. A water-cooled sampling probe was used to secure flue gas samples for smoke determinations which were made using an automatic-sampling Bacharach Model RXB smoke meter. Thermocouples embedded in the wall, optical pyrometer readings through observation ports, and gas temperature measurements using a high-velocity shielded probe provided temperature data. Gas analysis for O_2, CO_2, and CO was by the Orsat method. A Mast ozone meter, equipped with a scrubbing system to oxidize NO to NO_2, was used for measuring NO_2.

INITIAL FIRING AND DESIGN CHANGES

Initial firing of the burner for the combustion test rig showed that performance was excellent, considering that the fuel was No. 6 residual fuel oil fired at only 1.8 gph. In fact, if any problem existed, it was that this unit tended to produce better combustion than occurs in most industrial boilers (No. 2 Bacharach smoke at less than 10 percent excess air). The low smoke levels produced by this rig are the result of good mixing at the burner and fairly high flame temperature. Therefore, contrary to the usual burner development practice, modifications to the burner of the combustion rig were generally intended to produce combustion with higher smoke levels at a given excess air.

Atomization

The good combustion with short flames that characterized the early firing of this unit were attributed to unusually high turbulence levels for the conditions desired. Observations of the flame showed that this turbulence appeared to be generated by the high-velocity atomizing air from the fuel nozzle.

Several nozzles were tried in an effort to reduce turbulence. These included:

(1) An industrial air-atomizing nozzle designed to fire 2 to 10 gph of residual fuel (Delavan Industrial Airo nozzle No. 2125-10).

(2) A pressure-atomizing nozzle designed to fire 1.65 gph of distillate fuel oil (Monarch 80-degree spray angle, solid cone nozzle).

(3) A syphon-type air-atomizing nozzle designed to fire 1.0 gph of distillate fuel oil (Delavan SNA 1.00 nozzle).

The third of these nozzles gave performance nearest to the desired combustion pattern. Atomizing air openings in this nozzle appeared to be sufficient to provide good oil atomization, while the total quantity of atomizing air was sufficiently low to avoid excessive air turbulence in the flame zone. This nozzle was fired at 15 to 30 psig atomizing air pressure (design pressure is 3 to 5 psig) and oil was supplied at a rate of about 1.8 gph by a positive displacement pump.

For the trial firing at 7 gph, the industrial air-atomizing nozzle was reinstalled. This run was not specifically aimed at low-turbulence flames, but was intended to provide combustion at the high turbulence levels normally encountered in industrial units.

Burner Changes

After the initial firing, a slight modification was made to the burner itself. The refractory burner throat was lengthened from 4-1/2 inches to 9 inches (Figure 3 shows the 9-inch burner throat). The throat length had been initially limited to 4-1/2 inches to prevent loss of turbulence when firing with axial air. However, after firing the unit, it was observed that turbulence was adequate to permit lengthening the cone without sacrifice in flame quality.

Therefore, the throat was lengthened to 9 inches, equal to the thickness of the refractory end of the furnace, to minimize heat transfer into the burner structure.

The size and angle of the exit cone of the burner throat was also changed to optimize flame shape with swirl.

Addition of Cooling Surface

To lower average flame and surface temperatures in the combustion rig, a cooling surface was installed within the furnace. This surface consisted of three hairpin loops of water-cooled tubing which were laid on the bottom of the furnace. Total length of tubing within the furnace was about 40 feet. The tube diameter was 3/4 inch.

Installation of this cooling surface reduced gas temperatures near the center of the furnace from the range of 2300 to 2600 F to the range of 1600 F to 1650 F. As will be discussed in the following section of this report, this change resulted in increased smoke emissions at most excess air levels.

RESULTS OF COMBUSTION TRIALS

It should be pointed out that the scope of this task did not require extensive firing of the combustion rig or extensive emission measurements. Rather, the scope called for preliminary firing to ensure that the burner produced satisfactory combustion and that combustion conditions approaching those in an industrial boiler could be achieved.

Variables included within the combustion trials performed at Battelle included:

(1) Ratio of swirl air flow to axial air flow for combustion air
(2) Atomizing air pressure

(3) Fuel

(4) Presence of cooling surfaces to reduce furnace temperature.

These trials were conducted at a firing rate of about 1.8 gph residual fuel oil. In addition, one trial was made at a firing rate of about 7 gph. At this higher firing rate, turbulence levels would approach those present in an industrial boiler.

An analysis of the fuel oil used for this project was provided by the laboratory of an oil company. They reported the properties as follows:

Gravity, °API at 60 F	11.7
Viscosity, sec. Furol at 122 F	68
or sec Saybolt Universal at 100 F	1400
Sulfur, weight percent	0.63
Carbon residue, percent based on total sample	7.21

Based on these properties, the oil used for the combustion trials reported here was a light No. 6 fuel oil.

Effect of Combustion Air Swirl

The burner for this combustion test rig could be operated with various amounts of swirl imparted to the combustion air. This was accomplished by supplying various proportions of the combustion air through the swirl-air plenum and the axial-air plenum. The three combustion air swirl conditions generally used were as follows:

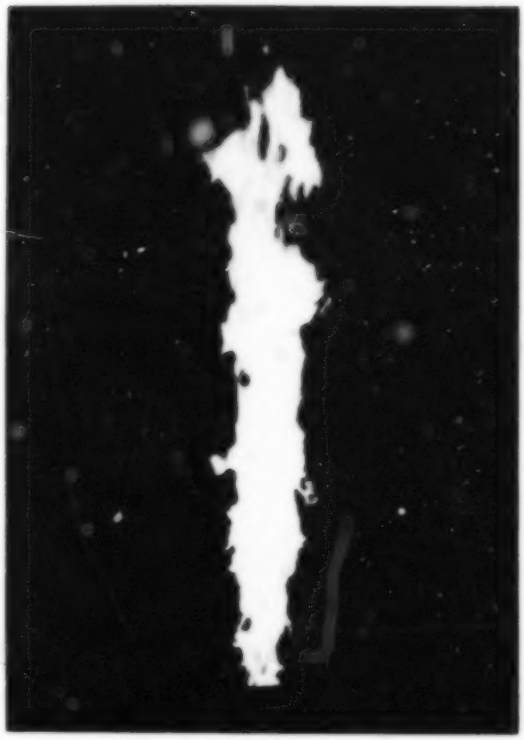
(1) All swirl - all combustion air fed through the swirl-air plenum and past the swirl vanes.

(2) All axial - all combustion air fed through the axial plenum and through the holes behind the burner throat.

(3) Swirl plus axial - approximately one-half of the air fed through the swirl-air plenum and one-half of the air fed through the axial-air plenum.

Figures 5, 6, and 7 show photographs of the burner firing about 1.8 gph of No. 2 fuel oil upward in the open at each of the above combustion-air conditions. Figure 5 shows the burner firing with all-swirl air which resulted in a short, fairly wide flame. Figure 6 shows the burner firing with all-axial air which produced a long,thin flame. Finally, Figure 7 shows the burner firing with 50-percent swirl air and 50-percent axial air and an intermediate flame.

FIGURE 5. BURNER FIRING FUEL OIL AT 1.8 GPH WITH ALL-SWIRL COMBUSTION AIR



IGURE 6. BURNER FIRING FUEL OIL AT 1.8 GPH WITH ALL-AXIAL COMBUSTION AIR

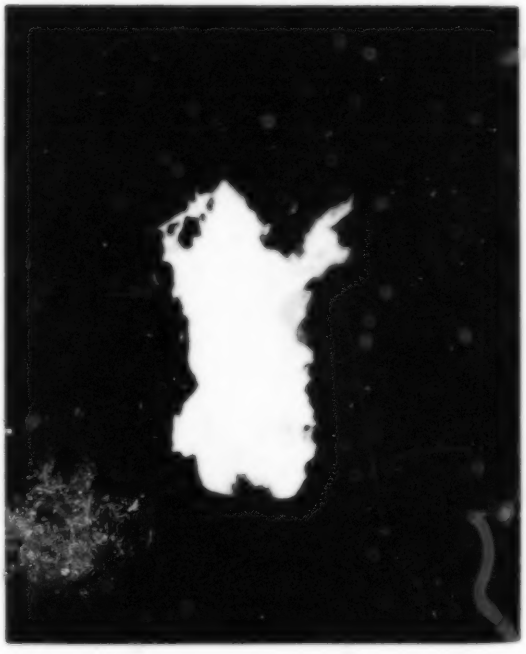


FIGURE 7. BURNER FIRING FUEL OIL AT 1.8 GPH WITH EQUAL QUANTITIES OF SWIRL AND AXIAL COMBUSTION AIR

Figures 8 and 9 show the relationship between Bacharach smoke number and oxygen in the flue gas (or excess air) for the three degrees of combustion air swirl. The data in Figures 8 and 9 were obtained at atomizing air pressures of 15 and 30 psig, respectively. Residual fuel oil was used for these trials at an atomizing temperature of 250 F.

At an atomizing pressure of 15 psig, the all-swirl flame produced significantly less smoke than the combination of swirl-plus-axial combustion air (Figure 8). Both the all-swirl and the swirl-and-axial flames produced clean combustion (less than No. 1 Bacharach smoke) at 10 percent excess air. A stable flame could not be obtained using only axial air.

At an atomizing pressure of 30 psig a stable flame was established at each combination of swirl air. Both the all-swirl and the all-axial flames produced slightly cleaner combustion than the combination of swirl and axial (Figure 9). Again, combustion was fairly clean with a No. 2 Bacharach smoke or less being recorded at an excess air of 10 percent.

Figures 10 and 11 show replotting of the data from Figures 8 and 9, but with atomizing air pressure as the variable. In both cases (all-swirl and swirl-and-axial), combustion at 15-psig atomizing air pressure was slightly cleaner than combustion at 30-psig atomizing air pressure in the area of interest (No. 1 to No. 4 smoke). This result is somewhat unusual as improved atomization (and improved combustion) is generally associated with higher atomization pressures. However, this nozzle was designed to operate at 3 to 5 psi and operating it at 30 psi may have disturbed the flame (by altering spray angle or generating excessive axial momentum) and adversely affected the combustion process. Also, the difference may not be too significant, partly because of the limited quantity of data and partly because of scatter in the data.

Because one objective of this program is to investigate any improvement in combustion and reduction of emissions as a result of burning emulsions,

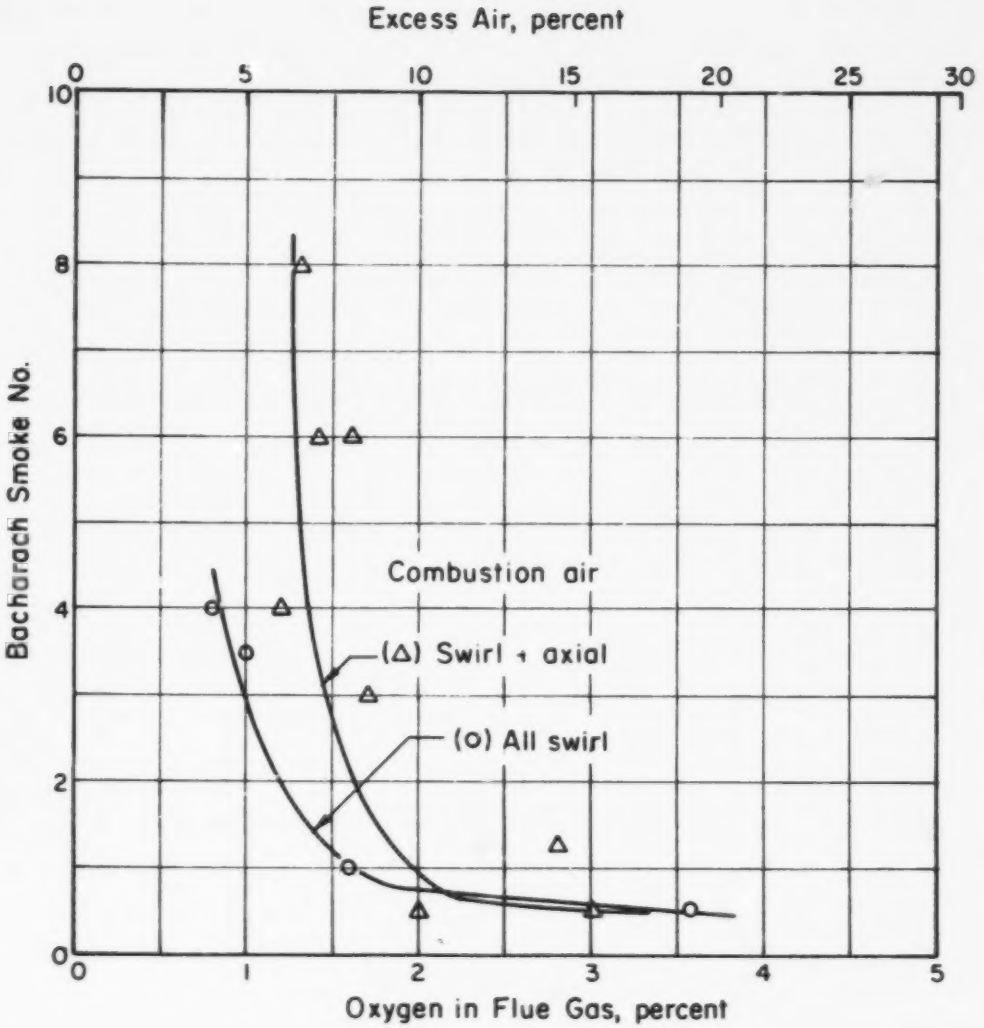


FIGURE 8. RELATION OF BACHARACH SMOKE NUMBER TO EXCESS AIR AND OXYGEN IN FLUE GAS

Fuel: No. 6 fuel oil
Fuel temp at nozzle: 250 F
Atomizing air pressure: 15 psig
Combustion air: as shown.

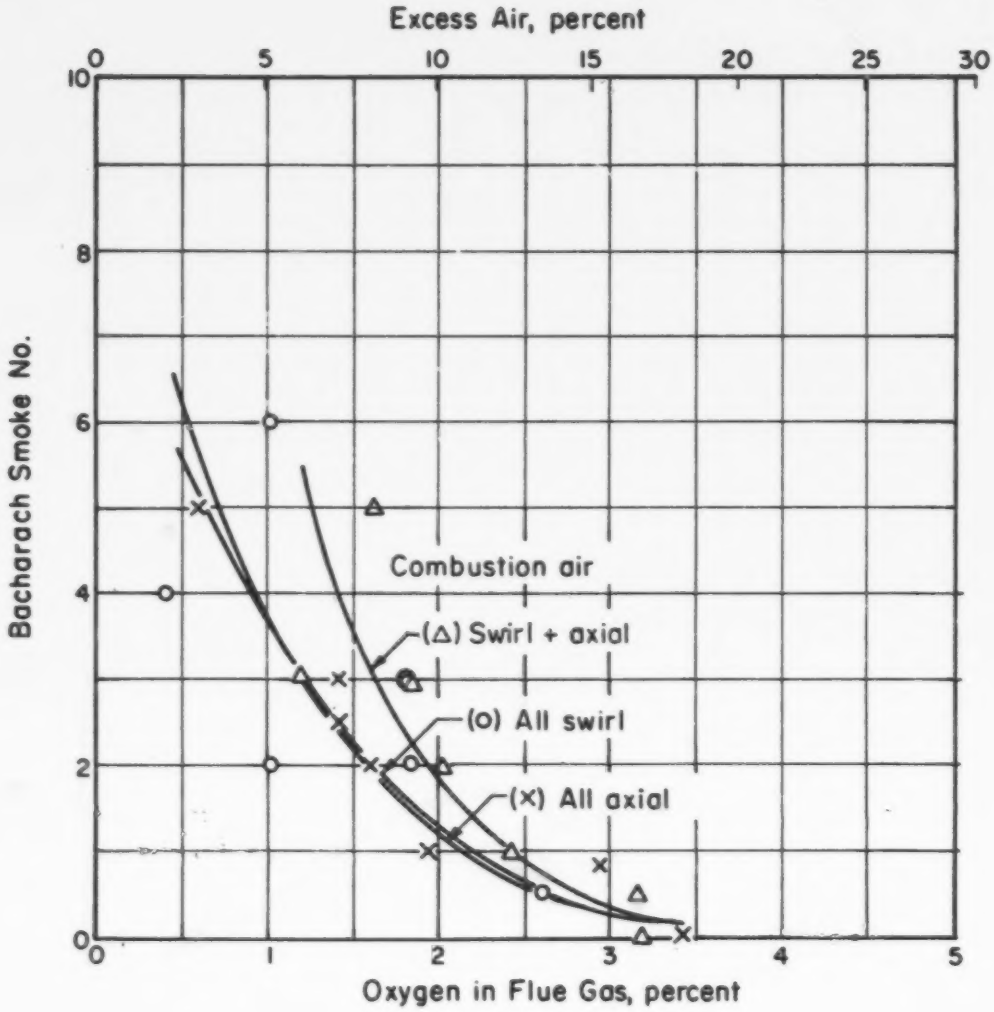


FIGURE 9. RELATION OF BACHARACH SMOKE NUMBER TO EXCESS AIR AND OXYGEN IN FLUE GAS

Fuel: No. 6 fuel oil
Fuel temp at nozzle: 250 F
Atomizing air pressure: 30 psig
Combustion air: as shown.

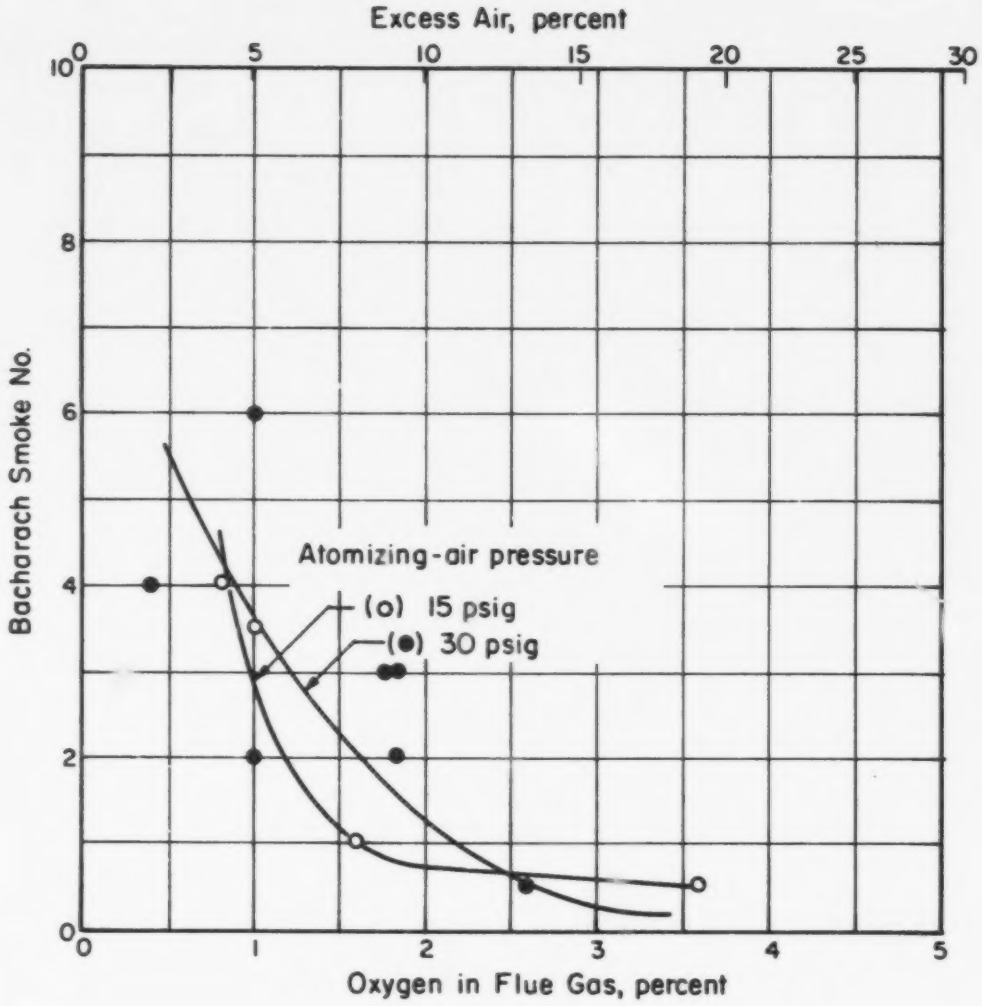


FIGURE 10. RELATION OF BACHARACH SMOKE NUMBER TO EXCESS AIR AND OXYGEN IN FLUE GAS

Fuel: No. 6 fuel oil
Fuel temp at nozzle: 250 F
Atomizing air pressure: as noted
Combustion air: all swirl.

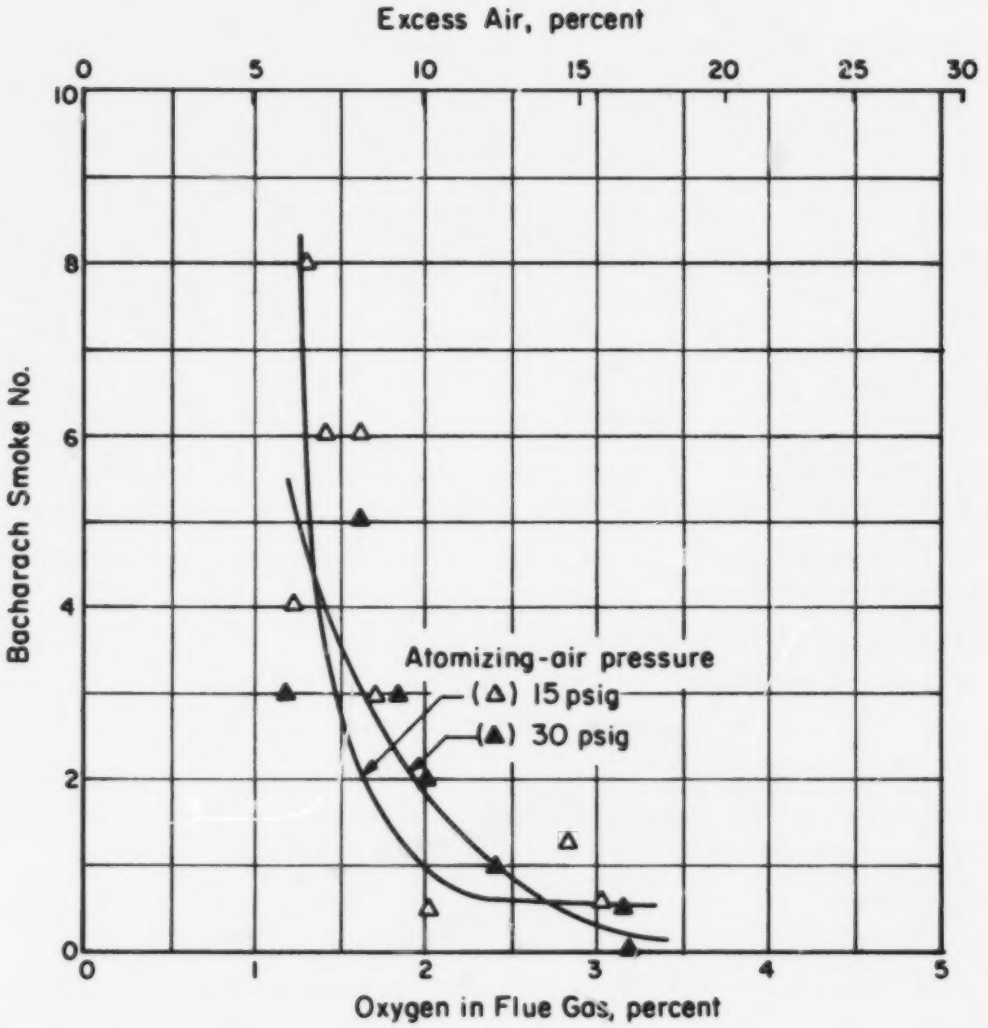


FIGURE 11. RELATION OF BACHARACH SMOKE NUMBER TO EXCESS AIR AND OXYGEN IN FLUE GAS

Fuel: No. 6 fuel oil
Fuel temp at nozzle: 250 F
Atomizing air pressure: as noted
Combustion air: swirl + axial.

it was decided to run the remaining trials with the burner adjusted to produce the highest smoke levels. Use of this flame would provide the maximum opportunity for observing improved combustion as represented by reduction in smoke levels. Therefore, except as noted, all combustion trials described in the remainder of this report were conducted with both swirl-and-axial air and at an atomizing air pressure of 30 psig. This flame appeared to be fairly stable.

Effect of Fuel Temperature

Figure 12 shows the data obtained while firing No. 6 residual fuel oil at oil temperatures in the nozzle of 180 F to 190 F, 220 F, and 250 F. For each of these trials, the combustion air was supplied by the combination of swirl-plus-axial air and the atomizing air pressure was 30 psig. Little significant difference in burner smoke could be detected when firing over this range of atomizing temperatures.

Based on data taken at one point (72 F using a Brookfield viscosimeter) and assuming that the viscosity of the oil used for these trials behaves in a manner similar to other residual oils, the viscosity at the firing temperatures was:

Oil Temperature, F	Viscosity, centistokes	Viscosity, SSU
72	1120	5200
180	36	162
220	18	86
250	12	56

The recommended viscosity range for firing boilers is 150 to 200 SSU for forced-draft boilers and 100 to 150 SSU for natural-draft boilers.[9] Except when firing at an oil temperature of 180 F, the viscosities for these trials were below the recommended values. For comparison, No. 2 distillate fuel oils are generally fired at a viscosity below 5 centistokes.

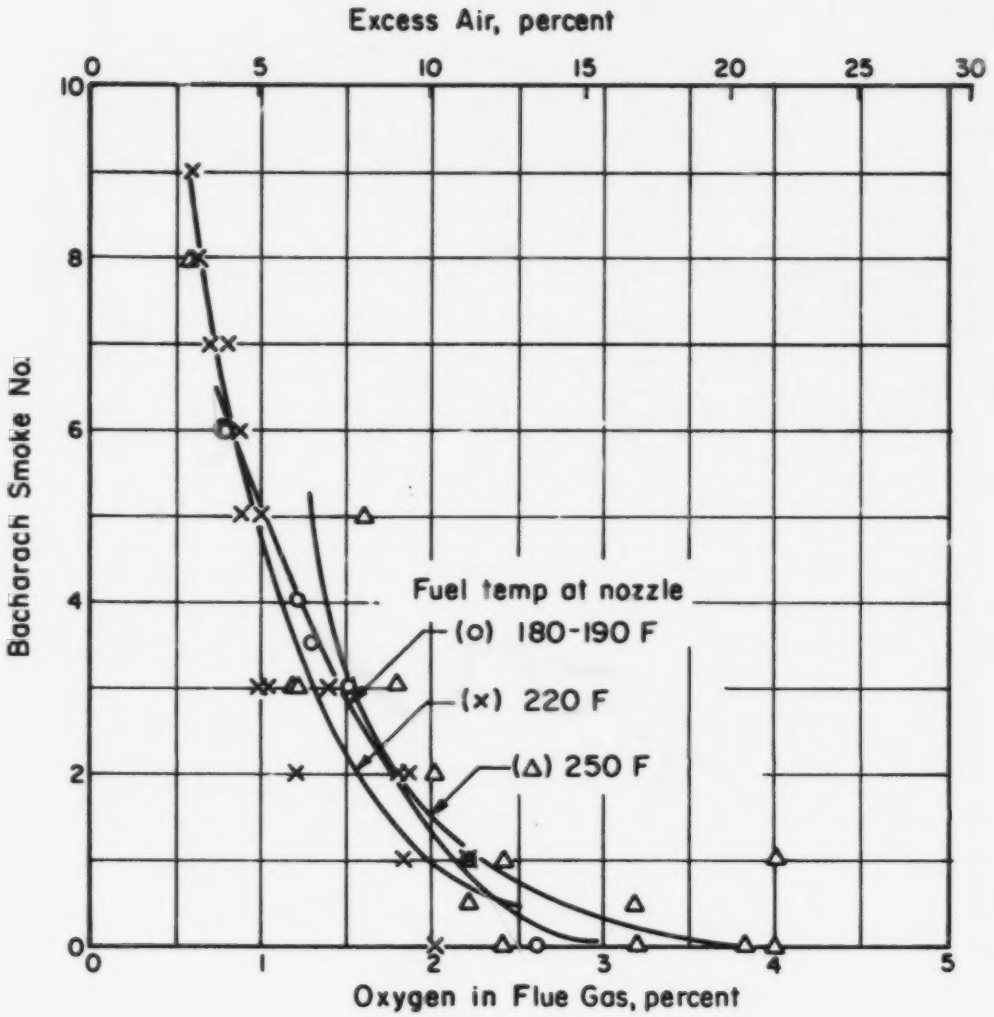


FIGURE 12. RELATION OF BACHARACH SMOKE NUMBER TO EXCESS AIR AND OXYGEN IN FLUE GAS

Fuel: No. 6 fuel oil
Fuel temp at nozzle: as shown
Atomizing air pressure: 30 psig
Combustion air: swirl + axial.

Firing Emulsified Fuel Oil

A sample of 20-percent water-in-oil emulsion was prepared from No. 6 residual fuel oil using the techniques outlined in the previous task report.[6] The emulsion appeared to be quite satisfactory and relatively stable.

Other techniques for preparing emulsions (besides using the Waring Blender) were considered because of the need for several gallons of fuel for each trial. A technique of simultaneously pumping heated fuel (160 F) through a positive displacement pump and mixing the fuel with a stirring rod driven by an electric drill motor appeared to produce satisfactory emulsions containing 20 percent water.

Viscosity of the 20 percent water emulsion was measured at 72 F. Assuming the viscosity of the emulsion varies with temperature in the same manner as the emulsified fuels investigated in the earlier program[6], the viscosity of this emulsion would be as follows:

Temperature	Viscosity, centistokes	Viscosity, SSU
72	3940	17000
180	66	300
220	28	133
250	18	86

A fuel temperature of about 250 F in the nozzle was selected as the maximum for these trials. Comparing the viscosities of the emulsified fuel with those presented earlier for the straight fuel, atomization temperatures of 220 F for the straight fuel and 250 F for the emulsions were observed to produce essentially the same viscosity. Therefore, at these temperatures, atomization characteristics (not including secondary atomization) of the two fuels should be about equal. Most trials were conducted at these temperatures.

Figure 13 shows the Bacharach smoke number measured at various excess air levels while firing the emulsified fuel at atomization temperatures of 220 F and 250 F. The trial at 250 F produced equivalent smoke at slightly lower excess air levels than the trial at 220 F, but the difference appears not to be significant.

Figure 14 shows the smoke number at various excess air levels while firing the straight fuel at 220 F and the emulsion at 250 F (equivalent viscosity). Firing the emulsion produced less smoke at all excess air levels above 4 percent. At excess air levels below 4 percent, the emulsion produced greater smoke. However, both fuels produced unacceptably high smoke emissions at these low excess air levels. Observations of the flame and general combustion conditions indicated that the emulsified fuel was much more sensitive to small changes in excess air than was the straight fuel.

NO_x Measurements

A few measurements were made of NO_x concentrations in the flue gas. Figure 15 shows the results of these data which must be considered quite preliminary. NO_x concentrations in the range of 350 to 425 ppm were measured while firing No. 6 fuel oil at an atomizing temperature of 220 F. As expected, NO_x emissions decreased as excess air levels were decreased. NO_x concentrations of 70 to 110 ppm were measured while firing the 20-percent water-in-oil emulsion at atomizing temperatures of 220 F and 250 F.

Wall surface temperatures in the furnace were measured with an optical pyrometer. At steady-state conditions, these temperatures reached about 2500 F when firing No. 6 fuel oil and reached about 2300 F when firing the emulsion. The lower temperatures when firing emulsion would be expected due to the presence of the water in the fuel. As lower flame temperatures generally result in lower NO_x production, the NO_x data correlate qualitatively with the temperature data. Although the magnitude of the NO_x reduction seems excessive, a small change of temperature in this range (2400 F) can significantly affect oxygen-atom

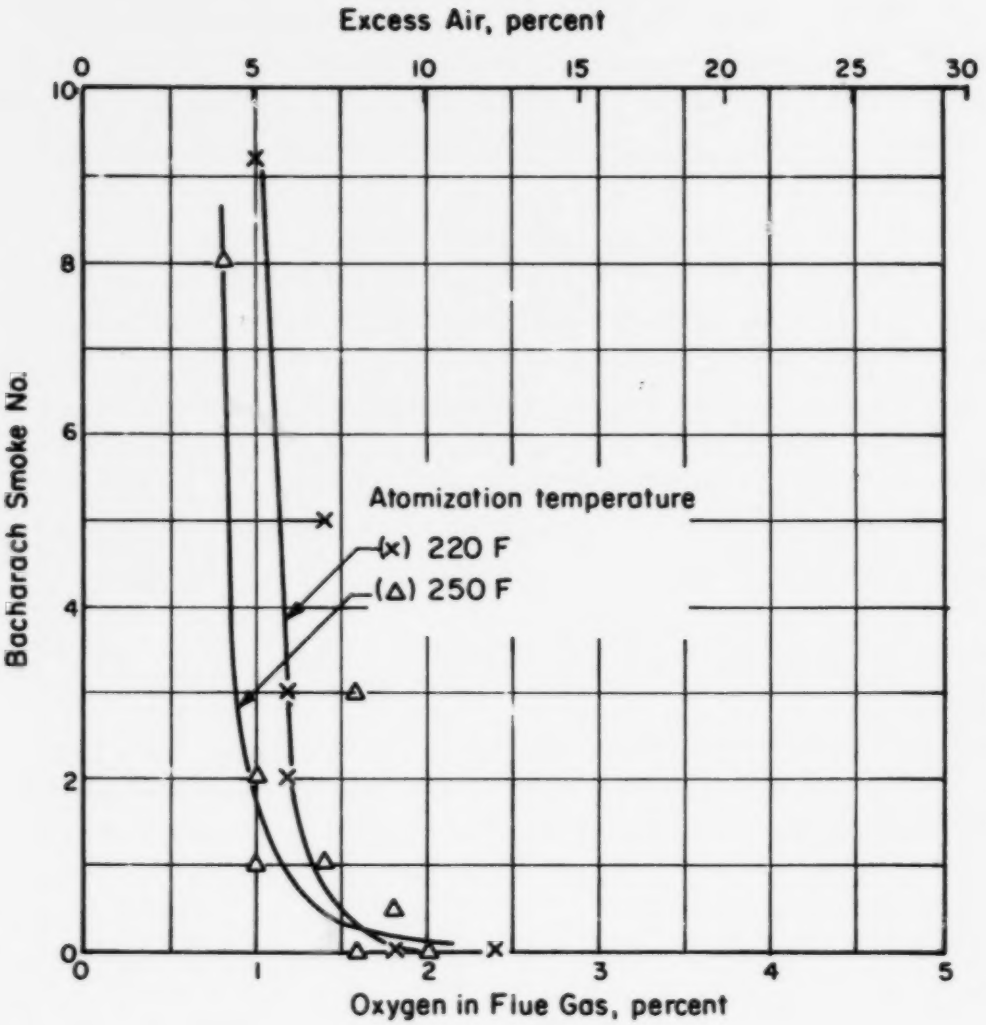


FIGURE 13. RELATION OF BACHARACH SMOKE NUMBER TO EXCESS AIR AND OXYGEN IN FLUE GAS

Fuel: 20% water in 80% No. 6 fuel oil emulsion
Fuel temp at nozzle: as shown
Atomizing air pressure: 30 psig
Combustion air: swirl + axial.

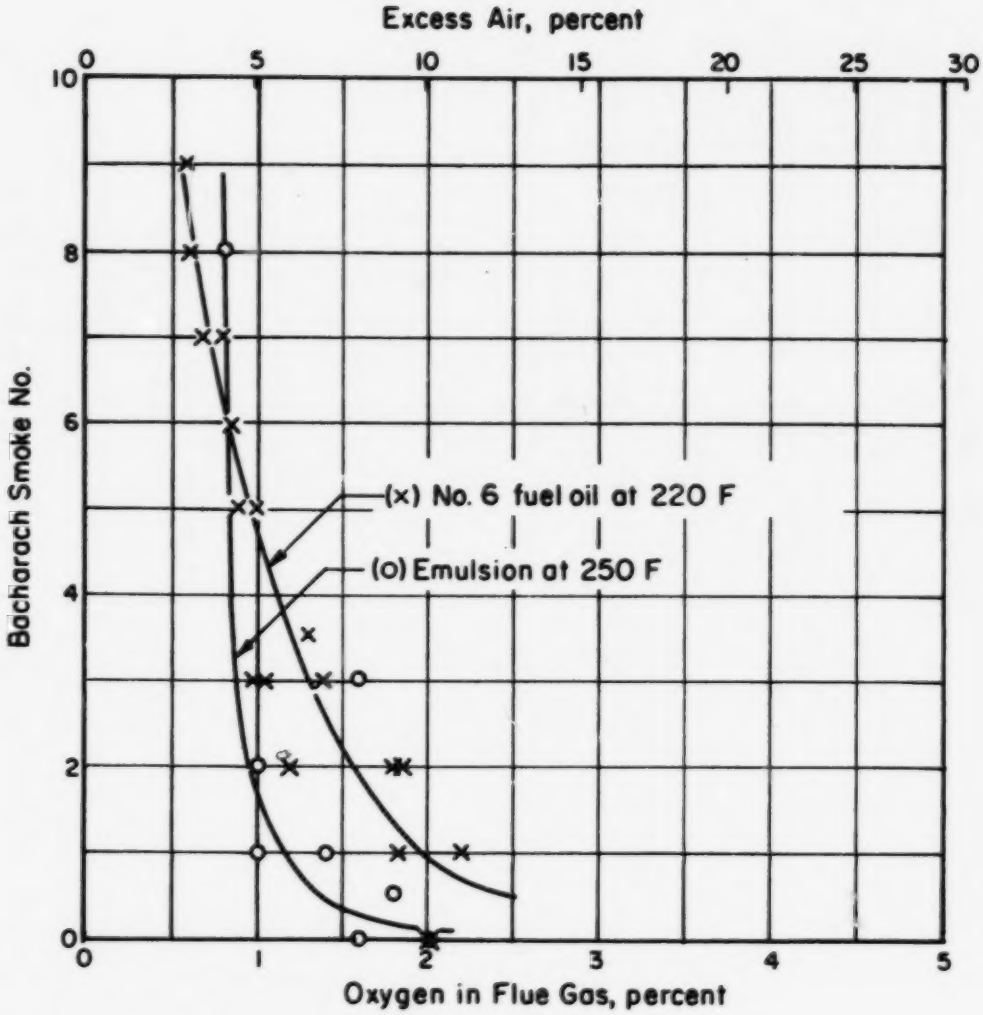


FIGURE 14. RELATION OF BACHARACH SMOKE NUMBER TO EXCESS AIR AND OXYGEN IN FLUE GAS

Fuel: as shown
Fuel temp at nozzle: as shown
Atomizing air pressure: 30 psig
Combustion air: swirl + axial.

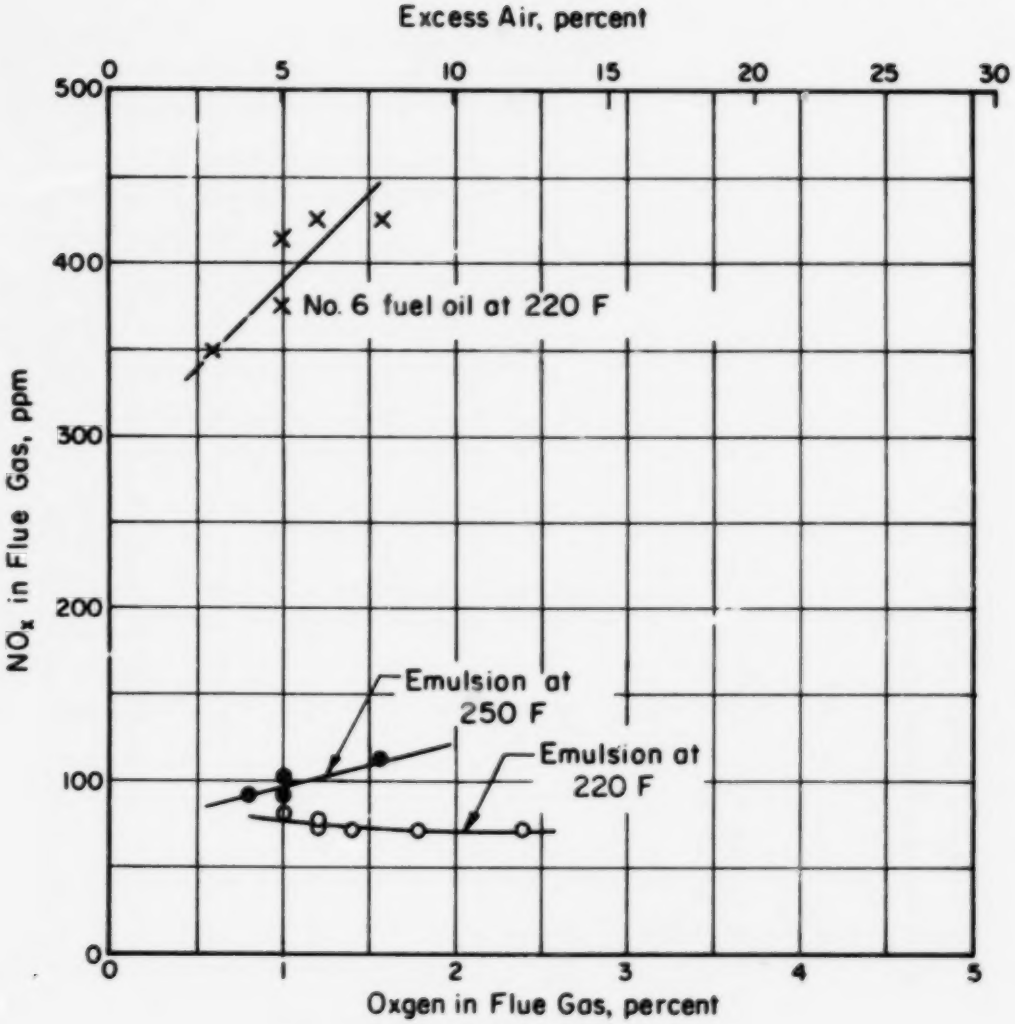


FIGURE 15. RELATION OF NO_x IN FLUE GAS TO EXCESS AIR AND OXYGEN IN FLUE GAS

Fuel: No. 6 fuel oil and emulsion
Fuel temp at nozzle: as shown
Atomizing air pressure: 30 psig
Combustion air: swirl + axial.

concentrations and, therefore, NO_x formation. Hence, NO_x reductions observed when firing emulsified fuels in this rig may not be directly applicable to other units with significantly different temperatures. Additional trials, as planned by NAPCA, will be required to refine these results.

Effect of Adding Cooling Surface

As stated earlier, combustion in the test rig constructed on this task order was generally excellent. In fact, combustion with residual fuel oil was better than is frequently obtained from firing distillate fuel oils. Consequently, it would be difficult to establish whether improved combustion occurred when emulsions were fired.

High wall and gas temperatures occurring in this rig were thought to be a significant factor in the low smoke output as relatively long residence time at high temperature permitted most smoke that formed to be burned. Therefore, it was decided to place a cooling surface inside the furnace to lower gas temperatures.

Three hairpin loops (40 feet) of 3/4-inch - diameter copper tubing were placed in the furnace. The loops were water cooled. Gas temperatures near the center of the furnace were measured at 2300 F to 2600 F without the cooling surface and 1600 F to 1650 F with the cooling surface.

Figure 16 shows the effect of the presence of the cooling surface on smoke emissions from the rig. All data were collected while firing No. 6 fuel oil at an atomizing temperature of 220 F. As expected, the smoke output of the rig increased by 1 to 2 Bacharach smoke numbers at all excess-air levels with the cooling surface present. Thus, installation of cooling surface provides another technique for altering combustion conditions with the combustion test rig to establish conditions desired for any particular trial.

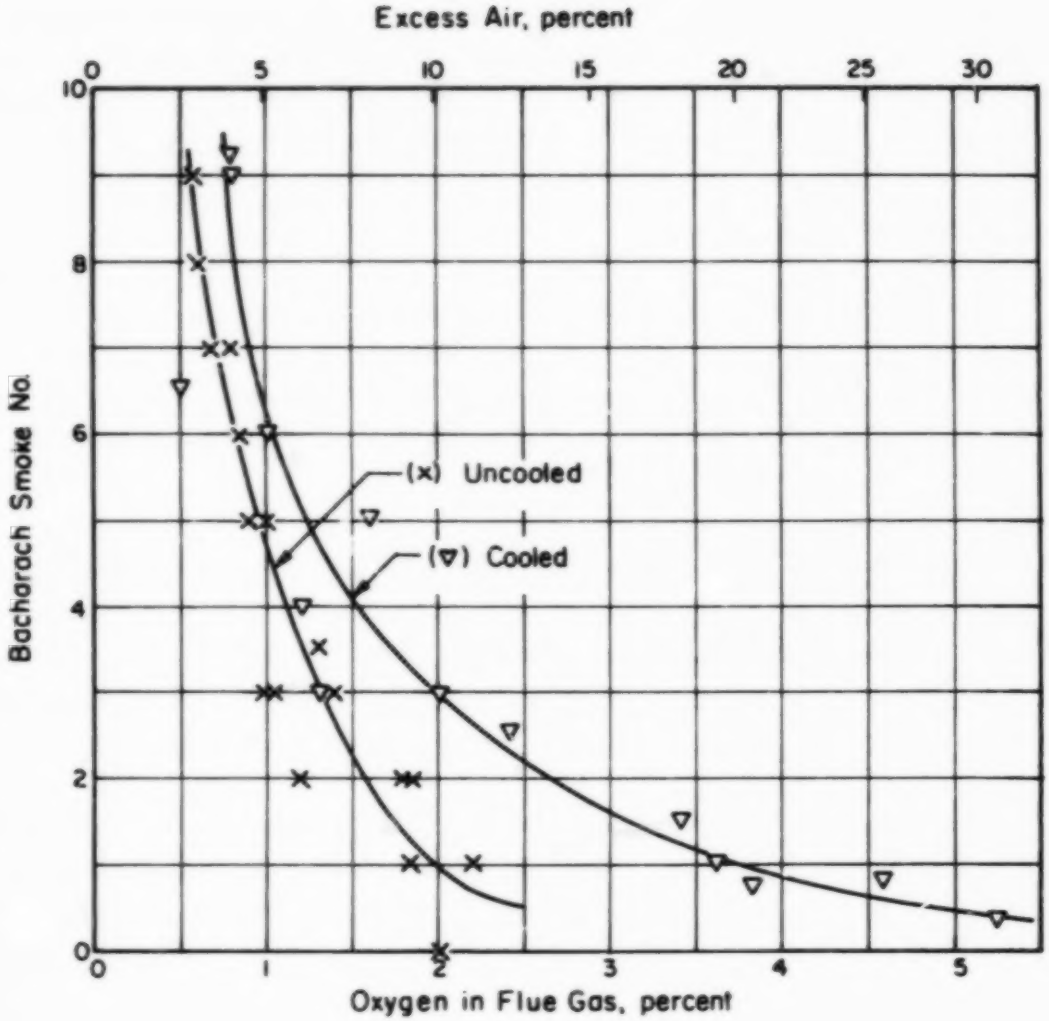


FIGURE 16. RELATION OF BACHARACH SMOKE NUMBER TO EXCESS AIR AND OXYGEN IN FLUE GAS

Fuel: No. 6 fuel oil
Fuel temp at nozzle: 220 F
Atomizing air pressure: 30 psig
Combustion air: swirl + axial
Cooled furnace.

NO_x measurements were not taken during these trials, but the NO_x concentration would be expected to be lower for the cooler furnace temperature.

Transient Combustion Trials

Several combustion trials were conducted as the furnace was warmed from a cold start to steady-state operating conditions. For these trials, the combustion air was set at values which would produce the desired excess air when the furnace reached steady-state conditions. Initial operation of the furnace during these trials produced high smoke levels. As the furnace warmed up, the smoke level decreased.

Figures 17 and 18 show results of two transient combustion trials firing No. 6 fuel oil. Initially, wall temperatures were low and smoke levels were high (No. 6 to No. 10). However, by the end of one hour, the temperatures and smoke levels were approaching their final values and the rate of change was low. Smoke levels approached No. 2 for the trial at 8 percent excess air (Figure 17) and approached No. 3 for the trial at 5 percent excess air (Figure 18).

Figure 19 shows similar data for a trial with a 20-percent water emulsion. As stated earlier, the smoke produced by burning the emulsion was much more sensitive to small changes in excess air that was the smoke from a No. 6 fuel oil flame. The scatter in the smoke data taken between 24 and 62 minutes further illustrates this point.

Firing at High Firing Rate

Only one trial was conducted at a firing rate in excess of 2 gph. This was primarily due to limitations imposed by the use of a simple uncooled exhaust stack.

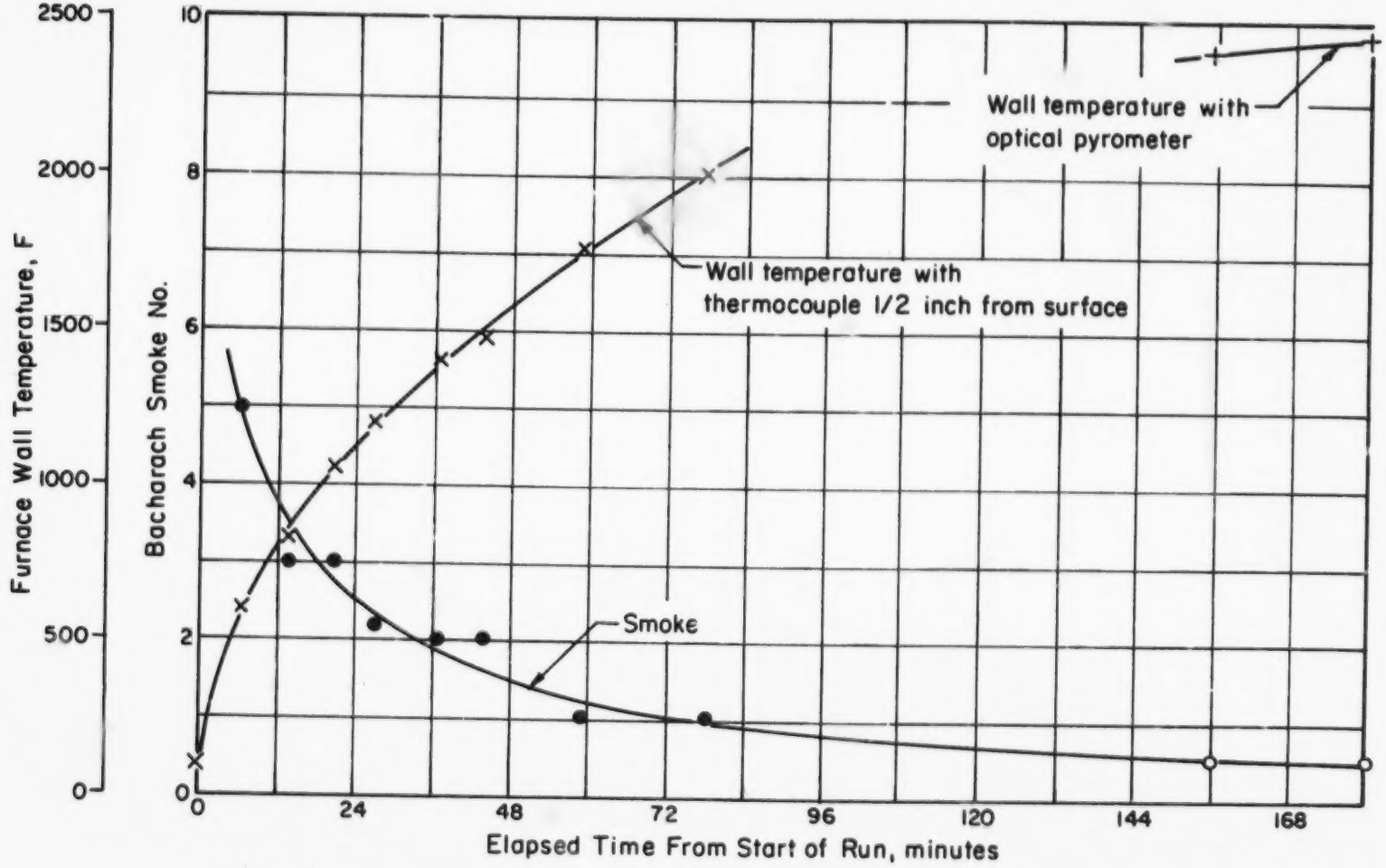


FIGURE 17. COMBUSTION CONDITIONS DURING FURNACE HEATING FROM COLD START

Fuel: No. 6 fuel oil
Fuel temp at nozzle: 220 F
Atomizing air pressure: 30 psig
Combustion air: swirl + axial, 8% excess air.

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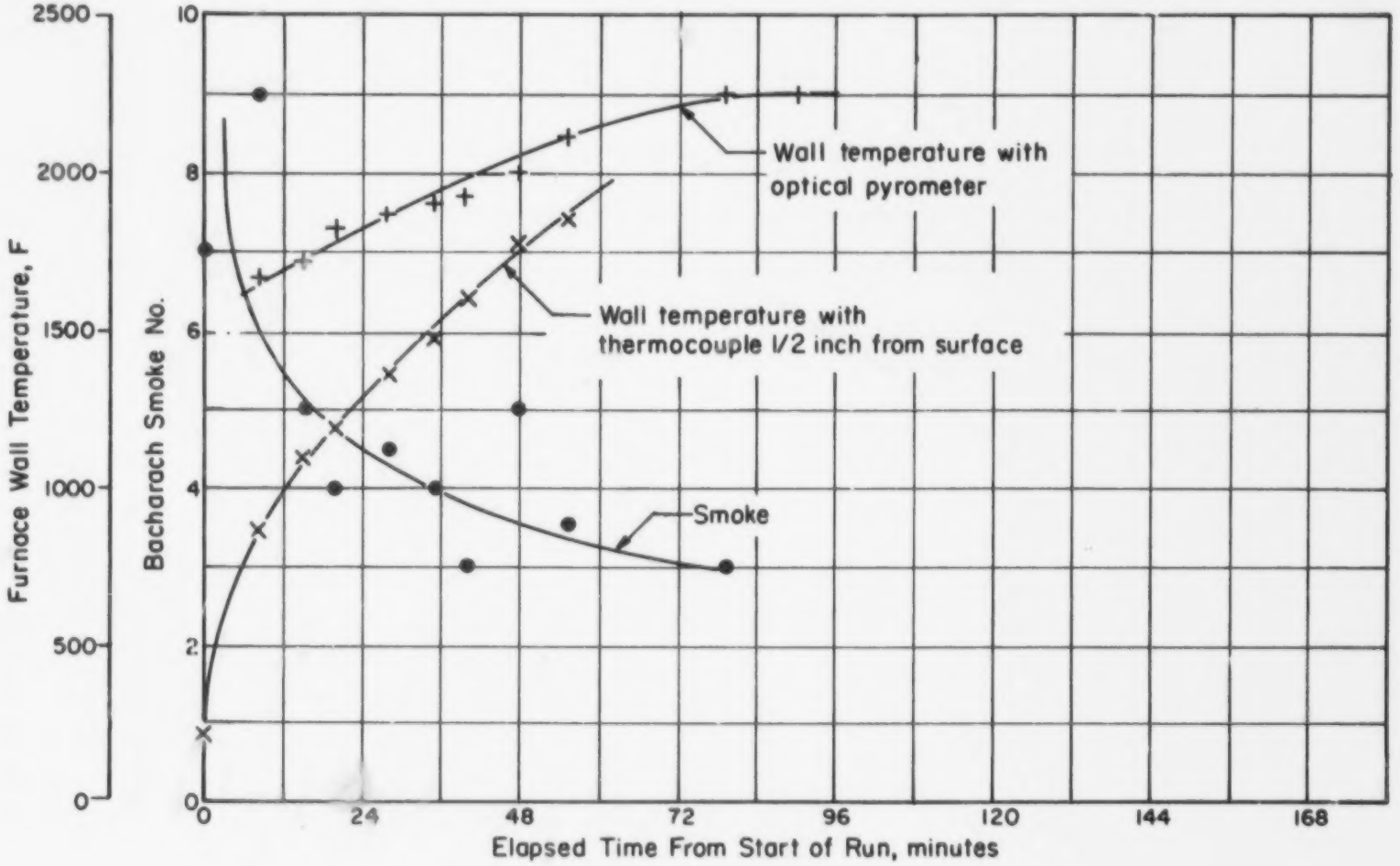

FIGURE 18. COMBUSTION CONDITIONS DURING FURNACE HEATING FROM COLD START

Fuel: No. 6 fuel oil
Fuel temp at nozzle: 210-215 F
Atomizing air pressure: 30 psig
Combustion air: swirl + axial, 5% excess air.

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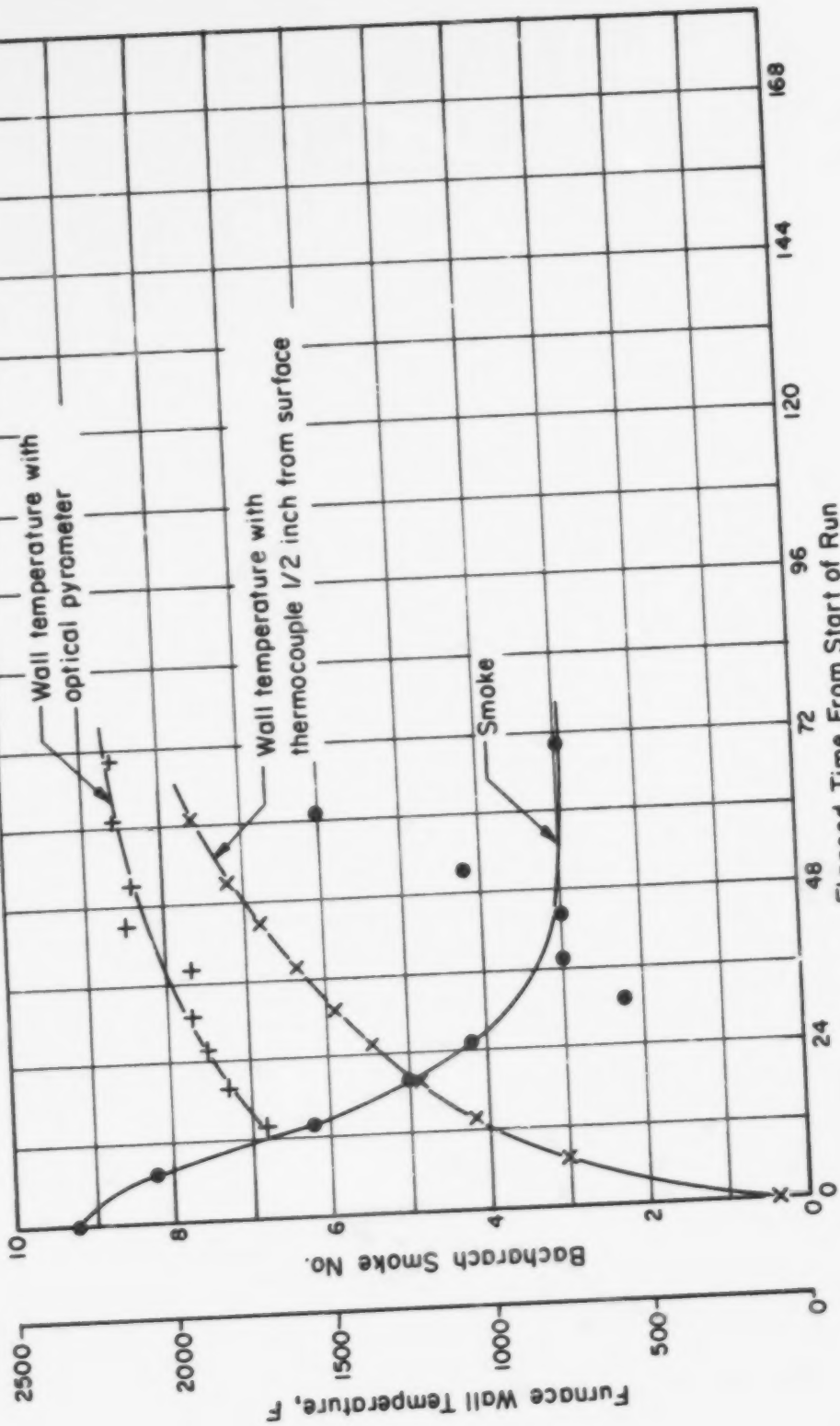

FIGURE 19. COMBUSTION CONDITIONS DURING FURNACE HEATING FROM COLD START

Fuel: 20% water in 80% No. 6 fuel oil emulsion
Fuel temp at nozzle: 250 F
Atomizing air pressure: 30 psig
Combustion air: swirl + axial, 6%.

The unit appeared to fire satisfactorily at a firing rate of about 7 gph. Firing at this rate was accomplished both with all-swirl combustion air and with all-axial air. Plenum pressures were 6.5 inches water for all-swirl burning and about 20 inches water for all-axial burning. The all-swirl flame appeared quite stable but the all-axial flame seemed to fluctuate somewhat. Data indicated the all-swirl flame burned with a No. 2 or less smoke in the range of 15 to 20 percent excess air.

Overall, it appears that this unit can be fired at rates up to at least 7 gph fuel oil and probably at rates to 10 or 15 gph fuel oil.

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(1) Wasser, J. H., Hangebrauck, R. P., and Schwartz, A. J., "Effects of Air-Fuel Stoichiometry on Air Pollutant Emissions from an Oil-Fired Test Furnace", Journal of Air Pollution Control Association, Vol 18, No. 5, pp 332-337 (May, 1968).

(2) Wasser, J. H., Martin, G. B., and Hangebrauck, R. P., "Effects of Combustion Gas Residence Time on Air Pollutant Emissions from an Oil-Fired Test Furnace", presented at NOFI Workshop, Linden, N. J., September 17 and 18, 1968, 19 pp.

(3) Martin, G. B., Wasser, J. H., and Hangebrauck, R. P., "Status Report on Study of Effects of Fuel Oil Additives on Emissions from an Oil-Fired Test Furnace", presented at 63rd Annual Meeting of the Air Pollution Control Association, St. Louis, June 14-18, 1970, 20 pp.

(4) Howekamp, D. P., and Hooper, M. H., "Effects of Combustion Improving Devices on Air Pollutant Emissions from Residual Oil-Fired Furnaces", presented at the New and Improved Oil Burner Workshop of the National Oil Fuel Institute, Tarrytown, New York, September, 1969, and at the 63rd Annual Meeting of the Air Pollution Control Association, St. Louis, June 14-18, 1970, 33 pp.

(5) Ivanov, V. M., Kantorovich, B. V., Rapiovets, L. S., and Khotuntsev, L. L., "Fuel Emulsions for Combustion and Gasification", Vestn. Akad, Nauk SSSR, No. 5, pp 56-59 (May, 1957).

(6) Ivanov, V. M., and Nefedov, P. I., "Experimental Investigation of the Combustion Process on Natural and Emulsified Fuels", NASA Tech. Transl. TT F-258, January, 1965, 23 pp.

(7) Barrett, R. E., Moody, J. W., and Locklin, D. W., "Preparation and Firing of Emulsions of No. 2 Fuel Oil and Water", NAPCA Contract No. PH 86-68-84, Task Order No. 8, November 1, 1968, PB-189075, 36 pp.

(8) Barrett, R. E., Moody, J. W., Hazard, H. R., Putnam, A. A., and Locklin, D. W., "Residual Fuel Oil-Water Emulsions", NAPCA Contract No. PH 86-68-84, Task Order No. 16, January 12, 1970, PB 189076, 83 pp.

(9) "Viscosity Temperature Relation for Fuel Oils", Chart published by Esso Research and Engineering, 1959, 1 p.

REB:HGH:CM:DWL/rd
July 15, 1970

APPENDIXES

A

APPENDIX A

BURNER CONSTRUCTION

Figure A-1 is a design drawing of the burner designed on this task order. The flame spreader was found not to be necessary when firing oil.

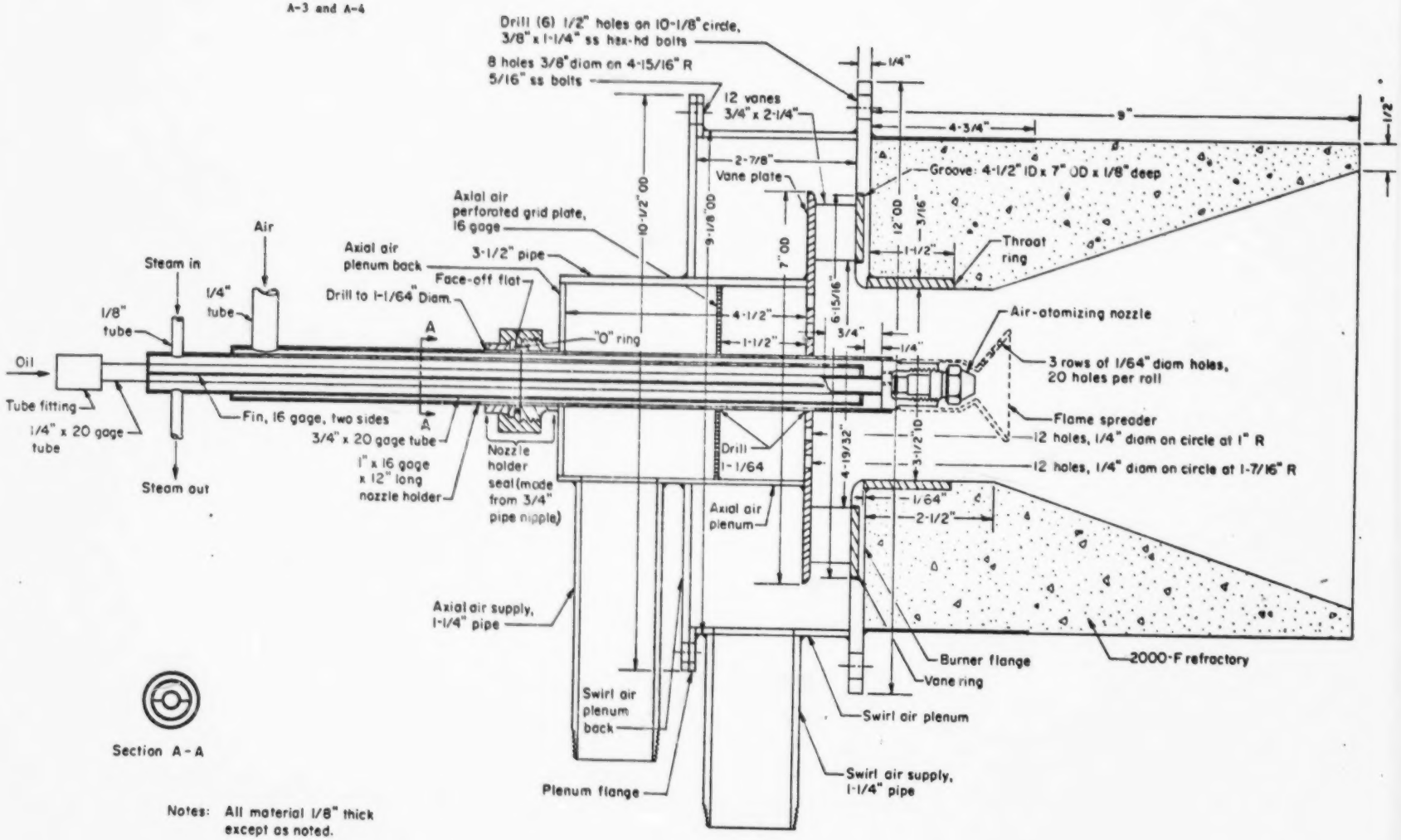
Figures A-2 through A-5 are photographs of various components of the burner and the complete burner as follows:

Figure A-2 - swirl vanes attached to the vane ring

Figure A-3 - completed swirl vane assembly

Figure A-4 - rear view of burner with the back of the axial-air plenum removed and the axial-air grid showing

Figure A-5 - front view of completed burner with refractory and flame spreader in place. The flame spreader was discarded later.



Notes: All material 1/8" thick except as noted.

FIGURE A-1. DETAIL OF BURNER FOR COMBUSTION RIG

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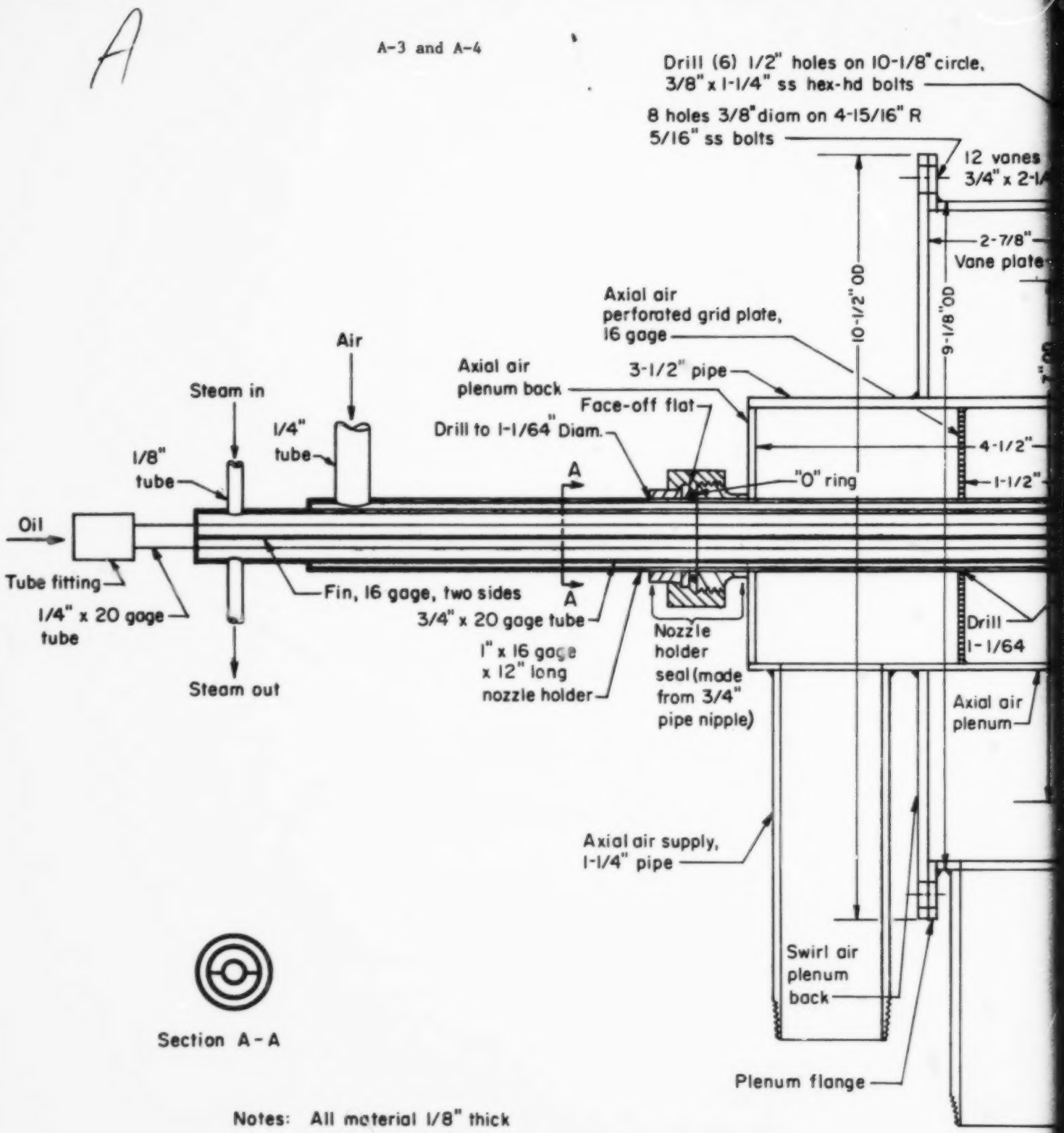

Section A-A

Notes: All material 1/8" thick
except as noted.

FIGURE A-1. DETAIL OF BURNER FOR COMBUSTION RIG

B

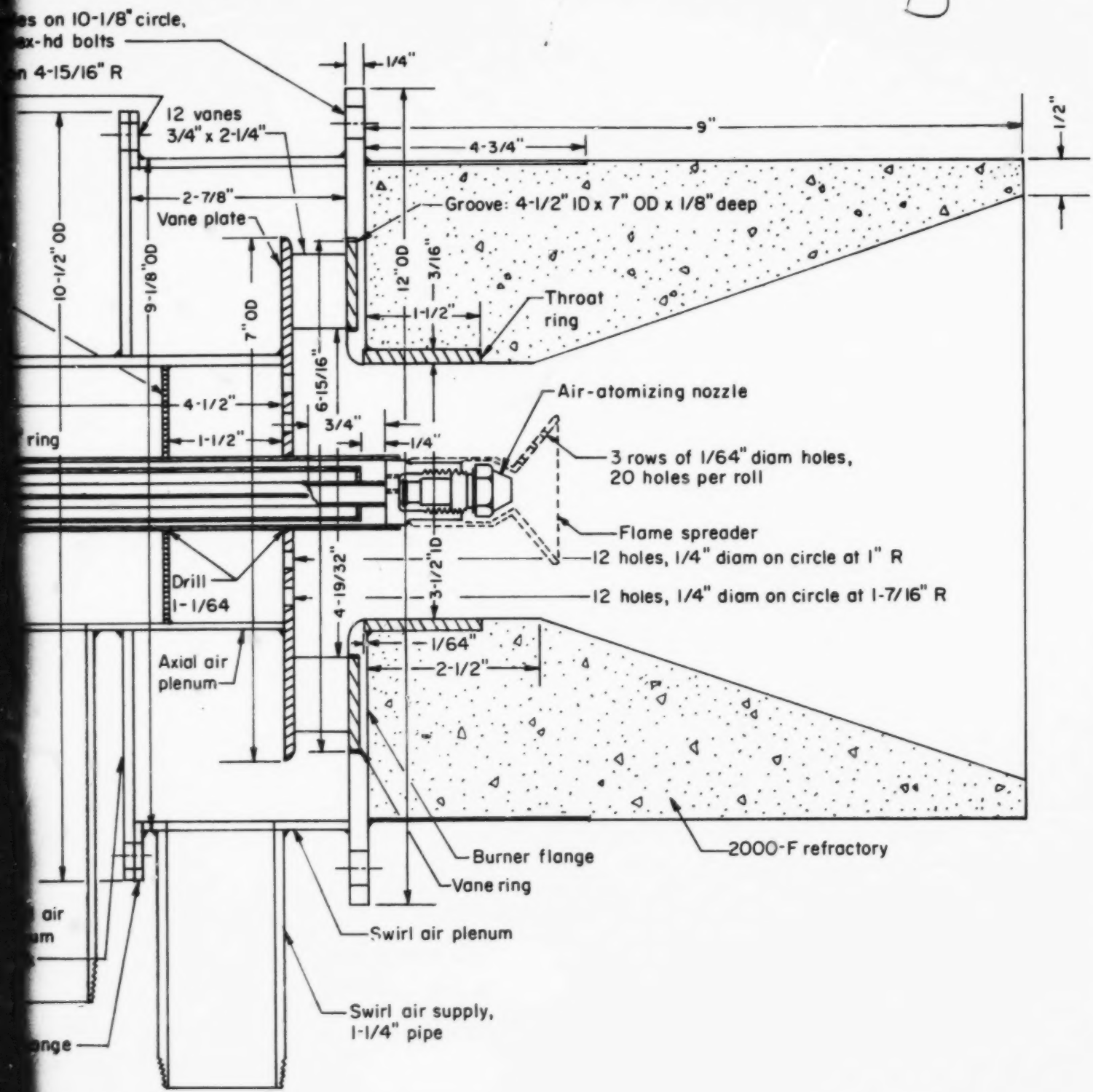
es on 10-1/8" circle,
ex-hd bolts
n 4-15/16" R
12 vanes
3/4" x 2-1/4"
1/4"
9"
4-3/4"
1/2"
2-7/8"
Vane plate
Groove: 4-1/2" ID x 7" OD x 1/8" deep
10-1/2" OD
9-1/8" OD
7" OD
12" OD
3/16"
1-1/2"
Throat
ring
6-15/16"
4-1/2"
1-1/2"
3/4"
1/4"
Air-atomizing nozzle
3 rows of 1/64" diam holes,
20 holes per roll
Flame spreader
12 holes, 1/4" diam on circle at 1" R
12 holes, 1/4" diam on circle at 1-7/16" R
3-1/2" ID
4-19/32"
Drill
1-1/64
1/64"
2-1/2"
Axial air
plenum
Burner flange
Vane ring
2000-F refractory
Swirl air plenum
Swirl air supply,
1-1/4" pipe

FIGURE A-2. SWIRL VANES IN PLACE

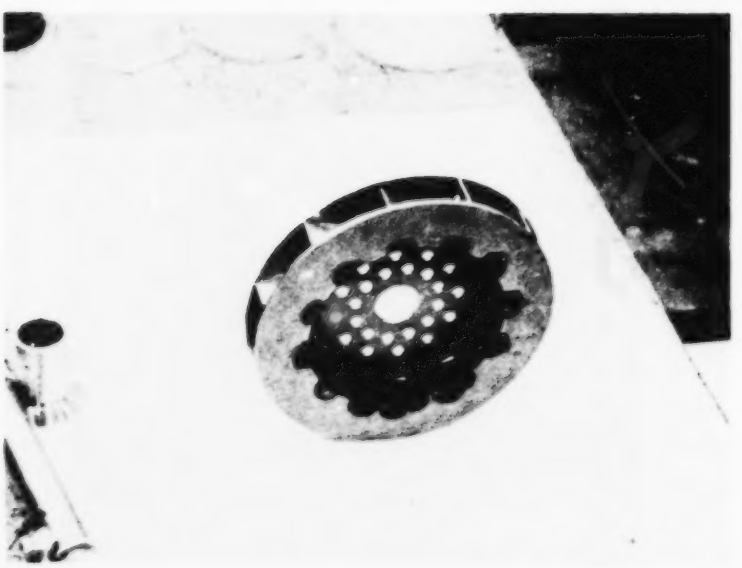

FIGURE A-3. SWIRL-VANE ASSEMBLY

FIGURE A-4. BACK VIEW OF BURNER WITH GRID EXPOSED

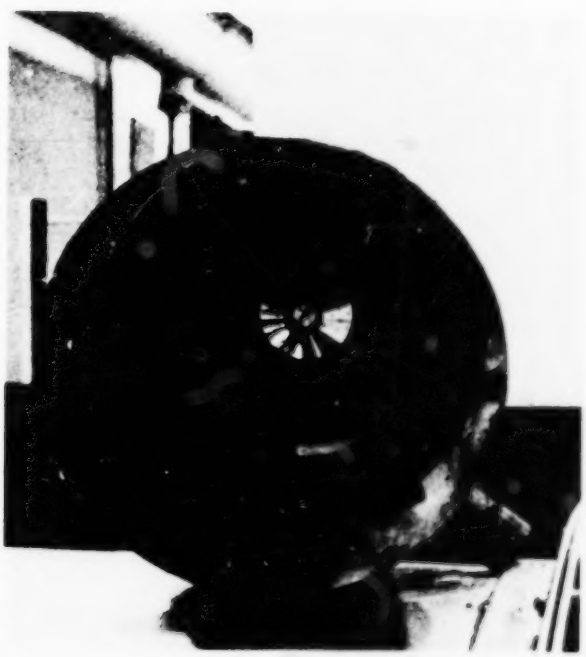

FIGURE A-5. FRONT VIEW OF BURNER WITH FLAME SPREADER IN PLACE

APPENDIX B

PROCEDURE FOR IGNITING FLAME

The following procedures for start-up were used during the preliminary combustion trials.

Heating and Circulating Oil

When firing residual oils that required preheating for proper atomization, it was necessary to heat the oil in the fuel-feed lines before attempting ignition. A valved by-pass line was connected to the fuel-feed line near the nozzle to permit recirculation of fuel to the tank until the fuel reached operating temperature. A valve was placed in the fuel-feed line between the by-pass line connection and the nozzle to permit shutting off the nozzle during the time the fuel was being heated and recirculated.

Ignition

A gas lance was used to ignite the flame in the furnace. This lance consisted of a 36-inch length of 1/8-inch pipe with four 1/8-inch-diameter holes about 1/2 to 2 inches from the end. The end of the pipe remained open. The lance was connected to the gas supply (natural gas or bottle gas) by flexible hose to permit inserting the lance into the furnace.

To ignite the furnace, the following procedure was used:

(1) Atomizing air was adjusted to about 25 to 50 percent of normal operating pressure (10 to 15 psi). This pressure varies with the nozzle type and size.

(2) The gas lance was ignited and inserted through the first view port (nearest the burner) so that the gas flame was near the centerline of the furnace.

(3) Fuel was supplied through the nozzle.

(4) At the first sign of flame, combustion air (either swirl or axial) was supplied.

(5) Atomizing air was adjusted to the desired pressure and the combustion air supply was increased until the desired excess air was reached or smoke disappeared.

(6) After the flame became stable, the gas lance was withdrawn.

(7) When the furnace reached operating temperature, the combustion air supply was adjusted to correct values for that trial.

When a flame-out occurred with a cold furnace, the fuel was shut off for 2 to 3 minutes to permit the furnace to clear of fumes. Air was supplied during this period.